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STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

GEOLOGY OF THE HEALDSBURG QUADRANGLE, CALIFORNIA

BULLETIN 161
1950

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DIVISION OF MINES
FERRY BUILDING, SAN FRANCISCO
OLAF P. JENKINS, Chief

San Francisco BULLETIN 161 July 1951

GEOLOGY OF THE HEALDSBURG QUADRANGLE, CALIFORNIA

By WILLIAM KELSO GEALEY

MINERALOGY OF THE CALIFORNIA GLAUCOPHANE SCHISTS

By GEORGE SWITZER

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LETTER OF TRANSMITTAL

To His Excellency
THE HONORABLE EARL WARREN
Governor of the State of California

Sir: I have the honor to transmit herewith Bulletin 161, *Geology of the Healdsburg Quadrangle, California*, prepared under the direction of Olaf P. Jenkins, Chief of the Division of Mines, Department of Natural Resources. The report is accompanied by a detailed geologic map of the quadrangle described, lithographed in colors, and represents one of the results of the Division's program of basic mapping in the State. The descriptions are illustrated by pertinent photographs and charts. The author, William Kelso Gealey, prepared the map and report as a Doctor's thesis at Cornell University. It covers a region in the northern Coast Ranges, including an interesting section of the Russian River. Economic deposits of quicksilver, sand and gravel, and crushed rock, as well as other deposits of potential value are described.

Together with this report is issued another paper, *Mineralogy of the California Glaucophane Schists*. The author, George Switzer, prepared this report while he was associated with Harvard University and later as a member of the staff of the Smithsonian Institution. The minerals which are described are of considerable scientific interest and distinctive of the California Coast Ranges province. Since most of these mineral deposits occur within the Healdsburg quadrangle, this report is included with the geologic description and map of the area.

Bulletin 161 should fill a long felt need for geologic and mineralogic information about Sonoma County in particular, and the northern California Coast Ranges in general.

Respectfully submitted,

Warren T. Hannum, Director
Department of Natural Resources

May 23, 1951

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GEOLOGY OF THE HEALDSBURG QUADRANGLE, CALIFORNIA *

By William Kelso Gealey **

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ABSTRACT

The Upper Jurassic Franciscan group, Upper Jurassic Knoxville formation, Cretaceous (?) conglomerate, Tertiary (?), late Pliocene Sonoma group, late Pliocene Merced formation, and Quaternary fanglomerate, terrace deposits, and alluvium, are exposed in the Healdsburg quadrangle.

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* This report represents a portion of a dissertation accepted for the requirements of the degree of Doctor of Philosophy in Geology, in the Graduate Division of Cornell University, Ithaca, New York.

** Geologist, Standard Oil Company, Taft, California.

Several episodes of folding and faulting have occurred. Post-Knoxville warping, probably with gentle folding, is first indicated, followed by a major folding with a N. 70° W. trend affecting the Mesozoic rocks before late Pliocene and referred to the upper Eocene and Oligocene interval. Minor folding, considered as lower Pleistocene, followed deposition of the Sonoma and Merced formations. The earliest faulting, during which two grabens were produced at Healdsburg, succeeded the major folding and is referred to the upper Eocene and Oligocene interval or later. Dip-slip faults, considered as middle Pleistocene, trend N. 40° W., and were formed during the early stages of uplift of the present ranges. Finally, a system of closely spaced major strike-slip faults trending N. 40° W. has fragmented the area. Activity along this system may have started in the middle Pleistocene; it has continued to the present. The movements have been largely horizontal and of a right-lateral type. Minor upward movements of the southwest sides also occurred. The strike-slip system is considered to be the important control of present topography and drainage in the northern Coast Ranges.

Uplift of the ranges since middle Pleistocene is reflected by a warped erosion surface, by wave-cut terraces along the nearby Pacific Coast, and, in the latest stages, by a series of terrace levels along the Russian River.

Quicksilver is at present being produced from the Mount Jackson mine, which, over the years, has accounted for a large share of the mineral production of Sonoma County. Sand, gravel, and crushed rock, suitable for construction purposes, are readily available within the quadrangle, and seven companies exploit them commercially. Many other valuable rocks and minerals are present, but in amounts too small to be commercial.

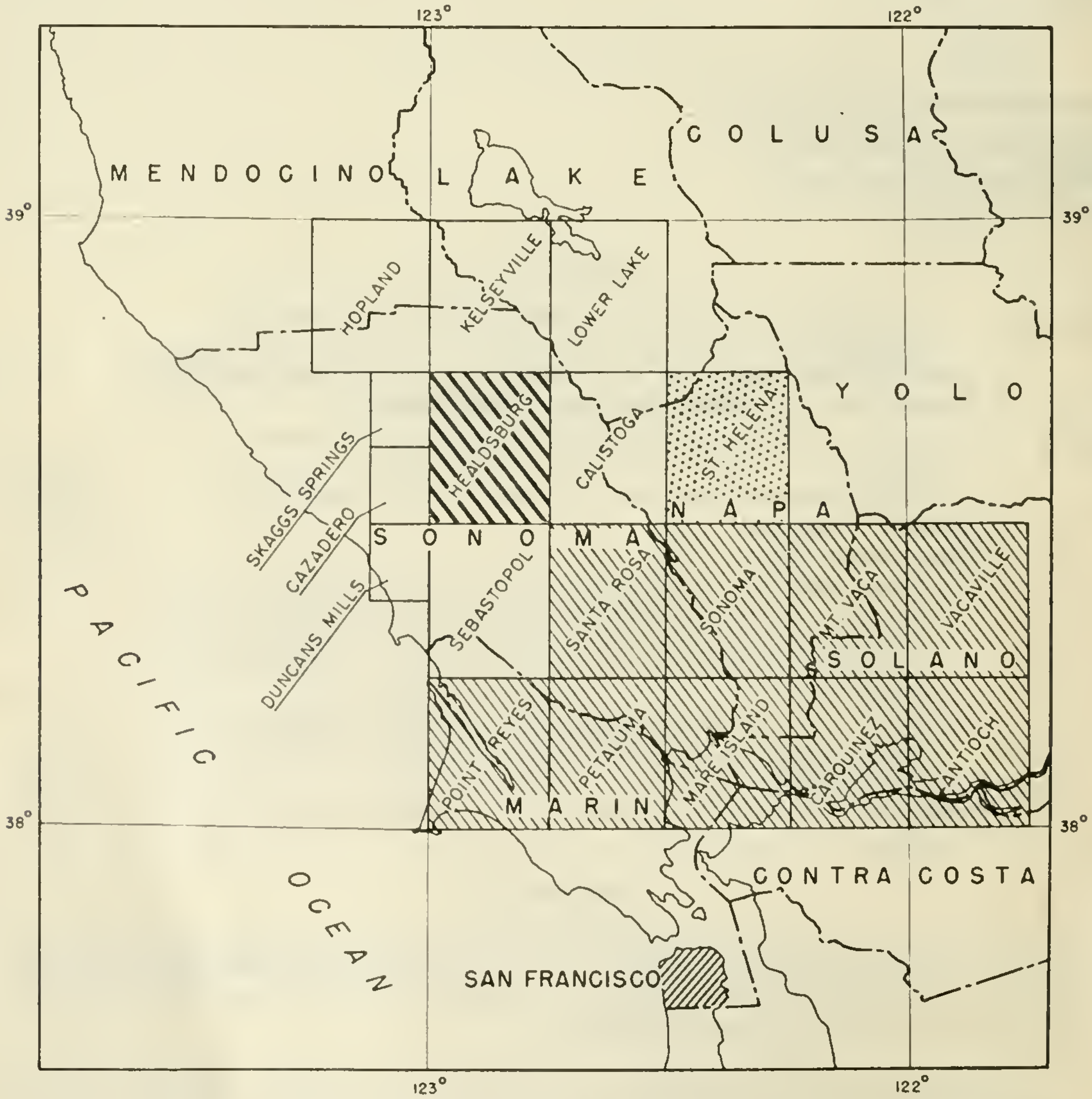

FIGURE 1. Index map showing location of Healdsburg quadrangle relative to the nine geologic quadrangles published in Division of Mines Bulletin 149 (shaded); the St. Helena quadrangle is now in preparation

INTRODUCTION

Field work upon which this report is based was done during a short interval in September 1947, from June to September 1948, and from July to October 1949. Mapping was done on aerial photographs, scale approximately 1:20,000; field mapping was reduced to the scale 1:62,500, and plotted on the U. S. Geological Survey topographic map of Healdsburg quadrangle.

For their kind assistance in this project, the writer wishes to thank Dr. C. M. Nevin and Dr. J. W. Wells of Cornell University; Dr. N. L. Taliaferro and Dr. J. Wyatt Durham of the University of California; Dr. Olaf P. Jenkins and Dr. Gordon B. Oakeshott of the California State Division of Mines; and the ranchers and townspeople in the Healdsburg area. Financial assistance was given by the Shell Oil Company fellowship in geology during the two years the writer spent at Cornell University.

The Healdsburg quadrangle covers the area 38° 30′ to 38° 45′ N. and 122° 45′ to 123° W., Mount Diablo Base and Meridian. Healdsburg, located nearly in the center of the quadrangle, is 63 miles northwest of San Francisco and 18 miles east of the Pacific Ocean.

Four topographic units, which directly reflect late Cenozoic structural evolution, are represented within the quadrangle. The mountains west of Dry Creek are the southward extension of the Mendocino Range, or Mendocino Plateau. Summit elevations are remarkably consistent, grading from 1,000 feet just west of Dry Creek Valley to 1,940 feet near the southwestern corner of the quadrangle. The western front of the Mayacmas Mountains, in the northeastern portion of the quadrangle, is a region of rugged topography, rising from 200 feet at Alexander Valley to 3,115 feet at Black Mountain. The narrow band of low hills (summit elevations 700 to 1,000 feet) that separates Alexander and Dry Creek Valleys is a distinct topographic unit within the Healdsburg quadrangle. The southeastern half is the northern end of the Sonoma Mountains; the northwestern half is a part of the Mendocino Range. It loses its identity just north of the Healdsburg quadrangle by blending into the Mendocino Plateau. The broad flat in the southeastern portion of the quadrangle is the northern extremity of Llano de Santa Rosa, which in its entirety is nearly 22 miles long, and 7 miles in maximum width; its surface is at an elevation of about 100 feet. Llano de Santa Rosa connects through a low gap at Penngrove with Petaluma Valley, which in turn joins San Pablo Bay. Except for its southernmost tip, which is drained by Petaluma Creek into San Pablo Bay, the Llano drains northward into Russian River.

The entire area of Healdsburg quadrangle is in the Russian River drainage area. Within the quadrangle itself, the Russian River changes from the course which it has maintained southeastward for nearly 50 miles, to swing due south along the northwestern edge of Llano de Santa Rosa, then flows westward through a deep canyon in the Mendocino Plateau, to reach the Pacific Ocean.

Some geological work bearing directly upon the geology of the Healdsburg area has been done. Osmont published two cross-sections of the northern Coast Ranges between the Pacific Ocean and the Great Valley, the northern of which passes through the southeastern corner of

Healdsburg quadrangle.[1] Holway,[2] in a study of the Russian River drainage, described many geomorphic features in the quadrangles; his conclusions regarding the development of the present Russian River are strongly supported by data in the present report. Dickerson [3] published geologic maps of the Santa Rosa–Petaluma–Point Reyes area, south of Healdsburg; his check list of Merced fauna includes a description of the Wilson Grove fossil locality, which is in the Healdsburg quadrangle. Watson [4] has mapped the geology of the central third of Healdsburg quadrangle; his map has been in part incorporated, with modifications, into the geological map of the present report; it included work done by Murray Nadler in the Geyserville syncline between Lytton and Canyon School.

F. A. Johnson [5] mapped northward from Dickerson's area, filling the geological gap to the south edge of the Healdsburg quadrangle. An investigation of quicksilver deposits of the region by the U. S. Geological Survey is the most recent work that has been done. E. H. Bailey's [6] paper on the western Mayacmas quicksilver district includes a geologic map which covers the northeastern corner of Healdsburg quadrangle (Black Mountain and Pine Flat) and an extensive area adjoining to the northeast. Myers and Everhart [7] studied in detail the Mount Jackson–Great Eastern mine, north of Guerneville, and included in their report a surface map of the immediate vicinity. The geology as mapped by Bailey and by Myers and Everhart is substantially that shown on the present geologic map.

STRATIGRAPHY

Many types of sedimentary and igneous rocks crop out within Healdsburg quadrangle. These are limited in age, with the probable exception of one conglomerate, to late Mesozoic and late Cenozoic. Between these two widely separated times, no deposition is recorded. The bulk of the rock which composes the Mendocino Plateau, the Mayacmas Mountains, and the north part of the low hill belt, belongs in the Upper Jurassic Franciscan group, the uppermost Jurassic Knoxville formation, and a probable Upper Cretaceous group. The southern portion of the central hill belt and the north end of Llano de Santa Rosa are covered by Pliocene sediments and volcanics of the Sonoma group, and the Merced formation, a local marine facies. Conglomerate and siltstone of uncertain age, probably Tertiary, and older than the Sonoma group, are preserved in a graben along Little Sulphur Creek. Quaternary deposits are fanglomerates, valley fill, and river terraces along present drainage.

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[1] Osmont, V. C., A geological section of the Coast Ranges north of the bay of San Francisco: Univ. California, Dept. Geol. Sci. Bull., vol. 4, no. 3, pp. 39-87, 1905.

[2] Holway, R. S., The Russian River, a characteristic stream of the California Coast Ranges: Univ. California, Pub. Geography, vol. 1, no. 1, pp. 1-60, 1913.

[3] Dickerson, R. E., Tertiary and Quaternary history of the Petaluma, Point Reyes, and Santa Rosa quadrangles, California: California Acad. Sci. Proc., vol. 11, pp. 527-601, 1922.

[4] Watson, S. E., The geology of part of the Healdsburg quadrangle, northern Coast Ranges, Sonoma County, California: Unpub. Master's thesis, Univ. California, Berkeley, California, 1941.

[5] Johnson, F. A., Petaluma region: California Div. Mines Bull. 118, pp. 622-627, 1943.

[6] Bailey, E. H., Quicksilver deposits of the western Mayacmas district, Sonoma County, California: California Jour. Mines and Geology, vol. 42, pp. 199-230, 1946.

[7] Myers, W. B., and Everhart, D. L., Quicksilver deposits of the Guerneville district, Sonoma County, California: California Jour. Mines and Geology, vol. 44, pp. 253-277, 1948.

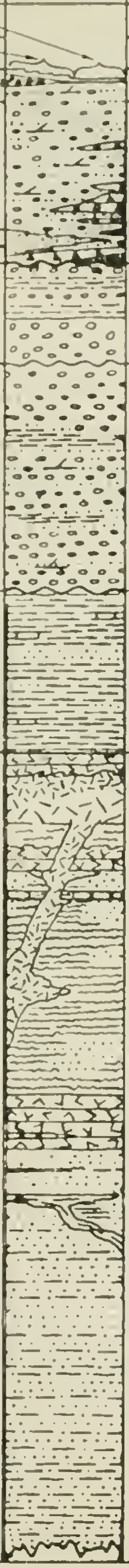
	EPOCH STAGE	GROUP FORMATION	SYMBOL	COLUMN	FEET	LITHOLOGY
QUAT.	Recent and Pleistocene	Alluvium	Qal			Sand and gravel
		Terraces	Qt		150	Sand and gravel
		Fanglomerate	Qf		50?	Sand and angular fragments
TERTIARY	Pliocene	Sonoma group	Ts		4,000 max	River gravel, sand, clay, interbedded tuff. Basalt flows at base Marine Merced sandstone to west.
		Merced fm.	Tm		500	
	?	Formation along Little Sulphur Creek	T		2,500+	Coarse red and gray conglomerate of Franciscan debris. Interbedded siltstone with limestone lenses. Foraminiferal.
CRETACEOUS (?)			K		5,000 min.	Massive cobble conglomerate. Rare shale lenses.
UPPER JURASSIC	"Tithonian"	Knoxville	Jk		4,000 est.	Thinly bedded dark gray shale, siltstone and sandstone interbeds Local thin fossiliferous limestone. (*Aucella piochii*)
	Portlandian	Franciscan group	gb sp ch sch gs Jf		20,000 min.	Medium to coarse arkose sandstone with minor shale. Greenstone and associated radiolarian chert. Intrusive sills of diabase, gabbro, and serpentized peridotite. Glaucophane and related schists.

FIGURE 2. Stratigraphic section, Healdsburg quadrangle

Franciscan Group

The Franciscan group, the oldest in the region, is exposed over more than two-thirds of the quadrangle. In addition, it probably underlies much of the area in which the Sonoma group is exposed at the surface.

The Franciscan group is an assemblage of clastic and chemical sediments, and intrusive and extrusive igneous rocks; it also includes some pneumatolytic metamorphic rocks developed from the other types. Within the area mapped, the assemblage is nearly 20,000 feet thick; it is typically developed, resembling closely the Franciscan as described by Lawson,[8] Davis,[9] and Taliaferro.[10]

Sandstone, Shale, and Conglomerate. Sandstones of the Franciscan group in Healdsburg quadrangle are arkosic, firmly cemented, angular, and medium to coarse-grained. Fresh specimens are gray to greenish gray; weathered specimens are buff or brown. Major constituents are quartz, which is most plentiful, fresh plagioclase, and some orthoclase; muscovite and biotite flakes and carbonaceous fragments are common; small flattened clay pellets and flecks are characteristic. In the coarsest sands, detrital black chert grains are an important constituent.

Much of the sandstone, particularly from the middle third of the Franciscan as exposed, shows no bedding whatsoever, so that the dip may have to be ascertained by close examination of flat shale flakes; and if shale flakes are absent or are very small, the dip may be unobtainable. Indeed, attempts to determine the attitude in several large, clean exposures of massive sandstone completely failed. Very rarely can top and bottom of beds be distinguished.

The massive sandstones are typically the coarsest; grains as much as 2 millimeters in diameter are present in a thick body in the ridge north of Porter Creek. More commonly, the sandstones are thick bedded, and contain thin intercalations of dark gray silty shale at intervals of from 1 foot to 4 feet. In the lower and upper thirds of the Franciscan section as exposed, silt and shale are prominent, and the rock is comprised of alternating 2- to 4-inch sandstone beds and 1- to 2-inch shale beds. Finer clastics in the Franciscan are dark gray silty carbonaceous shales, and some compact highly carbonaceous shales.

In the Healdsburg quadrangle, Franciscan conglomerates are uncommon; one fragmentary mass exists within the fault zone along the north branch of Saysal Creek; a second is present in a fault zone along Franz Creek just east of the quadrangle boundary; and a thin bed of pea gravel crops out north of Little Sulphur Creek. The conglomerate pebbles range from 1 inch to 6 inches in diameter; the matrix is a typical Franciscan arkosic sandstone. The pebbles are predominantly siliceous porphyries, but a few are diabase and basalt of Franciscan age. The pea gravel is composed of equal proportions of black and milky white vein quartz.

Crushing has been extreme in the Franciscan sediments. Small movements along many shear fractures have reduced much of the massive sandstone to small, smooth lozenges. Thin shales in thick-bedded sandstones have been squeezed along the shears at sharp angles to the original bedding. At one locality a shale layer 2 inches thick was squeezed several feet into two shear sets to form a perfect "X" in the massive sandstone.

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[8] Lawson, A. C., U. S. Geol. Survey Geol. Atlas, San Francisco fol. (no. 193), 1914.

[9] Davis, E. F., The Franciscan sandstone: Univ. California, Dept. Geol. Sci. Bull., vol. 11, no. 1, pp. 1-44, 1918.

Davis, E. F., The radiolarian cherts of the Franciscan group: Univ. California, Dept. Geol. Sci. Bull., vol. 11, no. 3, pp. 235-432, 1918.

[10] Taliaferro, N. L., Franciscan-Knoxville problem: Am. Assoc. Petroleum Geologists Bull., vol. 27, no. 2, pp. 109-219, 1943.

The clastics are by far the most plentiful constituent of the Franciscan group as a whole. In the area mapped, unaltered clastics aggregate some 12,000 feet in thickness; the glaucophane and related schists are in large part altered sandstone, so an original thickness of 16,000 feet of exposed shale and sandstone is indicated. The base of the group is not exposed.

Source of the material was granodiorite of a highland area west of the present coast line; climate of the source area was probably cool and moist.[11]

Cherts. Cherts are present at several horizons in the upper half of the Franciscan group, rythmically interbedded with thin siliceous shale. Individual chert beds average about 2 inches, but may be as much as 6 inches, in thickness; the more extensive chert bodies are from 50 to 200 feet thick. Red is the prevailing color, but green and white are common either in spots or as thin borders along fractures, indicating local reduction of ferric iron. The cherts are shattered, and the cracks are filled with white quartz. Some manganese is present as stains and incrustations of black oxide. A thin section shows the body of the chert to be amorphous silica, containing abundant tiny laths which appear to be zoisite. Radiolaria are scattered thickly, but the tests have been recrystallized to form a quartz mosaic. According to Davis,[12] the cherts were formed by deposition of colloidal silica from supersaturated sea water, the silica being furnished in emanations from submarine volcanic springs and lava outwellings. Wherever exposed in the area mapped, the cherts are stratigraphically either close to, in contact with, or included in greenstone.

The chert bed that crops out along the ridge crest south of Dorman Canyon is the only persistent one in the Healdsburg quadrangle. Other occurrences, as in Saysal Canyon, may represent remnants of extensive bodies, but fragmentation in the fault zones has left only small discontinuous patches exposed.

Greenstone. The term "greenstone" has been widely used to designate the fine-grained igneous rocks of the Franciscan group. Many of these rocks are so greatly altered that they cannot be identified microscopically. Others, though nearly fresh, are so fine-grained they cannot be classified in the field. The greenstone as mapped includes basalt, fine-grained diabase flows, dikes, sills, and a very small amount of agglomerate.

In the rugged terranes the greenstones form massive, resistant ridges with precipitous slopes. At lower elevations, however, they may underlie gently rounded hills, the igneous composition of which is indicated only by the characteristic reddish soil and scattered small fragments of bedrock.

Thick greenstones are associated with the diabase-gabbro sill that underlies Bradford Mountain. Thin sections show two types of greenstone, basalt and dacite; but these could not be distinguished in the field.

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[11] Taliaferro, N. L., Franciscan-Knoxville problem: Am. Assoc. Petroleum Geologists Bull., vol. 27, pp. 109-219, 1943.

[12] Davis, E. F., The radiolarian cherts of the Franciscan group: Univ. California, Dept. Geol. Sci. Bull., vol. 11, no. 3, pp. 235-432, 1918.

The basalts are dense, dark greenish gray and aphanitic, and are strongly sheared. They have been albitized and silicified by the intrusion of gabbro, so that the original texture has been destroyed. The rock now shows thin albite laths, magnetite granules, and epidote-chlorite clusters scattered through a groundmass partly recrystallized to quartz. Amygdules of calcite, chlorite, and actinolite are present.

The dacites are dense, dirty tan to dark gray, highly altered porphyries. In thin section, embayed phenocrysts of quartz, orthoclase, and oligoclase may be seen in a recrystallized groundmass of quartz. A single grain of augite was noted in one specimen. Tiny veinlets of calcite, chalcedony, opal, and in one case sphalerite and malacite, cut the groundmass.

The greenstones are present both above and below the sill, the portion above showing a few thin gabbro dikes along Pena Creek. Contact with the diabase phase of the sill is so difficult to detect that the whole igneous mass, excepting coarse gabbro, has been mapped as one unit. This same igneous group crops out in a syncline at the mouth of Porter Creek, and the assemblages at the two localities are considered to lie in the same general stratigraphic position.

Greenstones along Mill Creek and upper Porter Creek are altered basalts. The greenstones so extensively exposed along the mountain front east of Alexander Valley are all flow rock in which amygdaloidal zones occur. Thin sections of the dark red aphanitic rock that forms the ridge crest south of Saysal Canyon reveal a thoroughly albitized basalt, in which the original material has been altered completely to slender radiating albite aggregates and sphene clusters in a calcite matrix. Granular magnetite is scattered profusely throughout. This rock is cut by veinlets of calcite, chlorite, and chrysotile; vesicles have been filled by calcite, chlorite, chalcedony, and siderite.

Bailey [13] has described the igneous rocks which form the summit of Black Mountain. The upper (northeastern) portion is composed of a resistant agglomerate somewhat more siliceous than basalt, underlain by fine-grained tuffs in part silicified. The lower portion is diabase with some gabbro developed locally; it appears to be intrusive. Here, again, is an assemblage very like that of Bradford Mountain.

All the greenstones are veined by chalcedony and calcite, and at one locality by cross-fiber chrysotile. Flow structure is absent, so attitudes can be determined with confidence only where cherts are closely associated with the massive greenstones. Pillow structure, which is common in Franciscan extrusives elsewhere, was recognized at only one place in the Healdsburg quadrangle—a small exposure in the tributary to Porter Creek, in the NE$\frac{1}{4}$ sec. 13, T. 8 N., R. 10 W. Bailey reports that pillow structure is also common in a greenstone belt immediately to the east of the quadrangle.

The structureless character of the igneous bodies precludes accurate thickness determinations. Maximum thickness at Bradford Mountain is estimated to be 1,500 feet; at the mouth of Porter Creek 1,000 to 1,500 feet; along the mountain front east of Alexander Valley a maximum of 3,200 feet; and on Black Mountain at least 2,400 feet. Thickness changes rapidly along strike.

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[13] Bailey, E. H., Quicksilver deposits of the western Mayacmas district, Sonoma County, California: California Jour. Mines and Geology, vol. 42, pp. 199-230, 1946.

The greenstones are characteristic of the upper half of the Franciscan, and are most widely developed near the Franciscan-Knoxville contact. In addition to the localities already mentioned, numerous small greenstone bodies are present as isolated fragments in the major fault zones.

Amygdaloidal structure, locally, in the massive greenstones, and the association with tuffs and agglomerates indicate the effusive nature of the group. The intimate association with radiolarian cherts places the environment as submarine, at least in large part.

Gabbro and Diabase. Thick sills ranging in texture from finely diabasic at the top to finely granitic at the base underlie Bradford Mountain, the syncline at the mouth of Porter Creek, and Black Mountain. The diabase is a dark greenish-gray compact rock which in thin section shows a mesh of euhedral andesine crystals enclosing interstitial augite. Ilmenite is present as scattered laths. Most of the augite is partly altered to chlorite; some of the ilmenite is altered to leucoxene.

The gabbros are massive light- to dark-gray holocrystalline rocks containing crystals ranging from 1 millimeter to 2 millimeters in diameter. As determined by microscopic examination, the bulk of the gabbro originally averaged about 50 percent labradorite and 50 percent pyroxene. Augite with diallage parting is characteristic, but enstatite or hypersthene may occur in small amounts. Ilmenite may be present. The augite commonly shows partial replacement by late magmatic hornblende, and in one specimen has been altered by hydrothermal action to uralite. Secondary chlorite has developed from both augite and hornblende; leucoxene had developed from ilmenite.

Important exceptions to the above general composition are found. The lower portion of the gabbro body north of Dorman Canyon is olivine-rich, the olivine appearing in hand specimens to make up as much as a third of the rock. Both at Dorman Canyon and Porter Creek, the basal zone immediately adjacent to underlying serpentine is a pure enstatite rock.

Flow layering was observed in gabbro at one locality only. At Bradford Mountain, thin pegmatite dikes cut the rock.

The sill at Bradford Mountain is approximately 2,000 feet thick; that at the mouth of Porter Creek is 450 to 1,800 feet thick. At Black Mountain, slides and faulting have so complicated the picture that no satisfactory thickness determination is possible.

The prominent diabase-gabbro sills are high in the Franciscan, those at Bradford Mountain and Porter Creek being near the Knoxville contact. In addition to these large bodies, a few small diabase blocks are present in the fault zones east of Alexander Valley and in the Franciscan area west of Rogers School.

The areal relationship of the gabbro-diabase to overlying greenstone suggests that sill emplacement was localized at the base of the thick extrusives. The observed textural coarsening downward in the sills may be explained by the vastly greater time involved in the cooling of the central and lower portions. Considerable differentiation might be expected in sills of the dimensions these have. The common gabbro, olivine-rich gabbro, enstatite rock, and serpentinized peridotite are regarded as gravity differentiates from a single magma type during and after emplacement of the sills. Density of the rock types increases in the order given above, as judged by the field relationship.

The small diabase bodies present in the various fault zones may be fragmented plugs and feeder dikes. However, structural complications have obscured their realtionship to the country rock.

Serpentine and Peridotite. Bodies composed of massive boulders of greenish-black serpentinized peridotite enclosed in a bright bluish-green to pistachio-green matrix of smeared and slickensided flaky serpentine are common. The surfaces of the boulders are colored brown or yellow by concentrations of limonite; the interiors are commonly shattered and shot full of tiny cross-fiber chrysotile veinlets. Fresh surfaces show innumerable brightly reflecting cleavage planes on large crystals of bastite-antigorite replacing enstatite. The boulders, which range from 2 to 4 feet in diameter, weather less readily than the enclosing flaky serpentine, and lie scattered over the serpentine terrane as residuals.

The serpentinized peridotite boulders represent knots that preserve the original igneous texture. During serpentinization and subsequent crushing by regional shearing, the bulk of the original peridotite was reduced to the flaky serpentine matrix. Those few boulders which survived as massive knots after serpentinization were preserved from the later shearing effects by a buffer action of the matrix. Some of the thin serpentine smears along faults are entirely of the flaky variety. In a few localities, small segregations composed entirely of coarsely crystalline enstatite are included within serpentine.

Microscopic examination of the boulder rock shows its composition to be about 65 percent olivine, 35 percent enstatite, and some augite. Accessory minerals are picotite and chromite, in rounded grains. Only specimens of the least altered rock show the original olivine and pyroxene. In most cases, serpentinization has been complete, the olivine being changed entirely to mesh-work antigorite, the enstatite to bastite antigorite.

The extreme shearing universal in the serpentine bodies obscures their true attitudes. As judged by the structure in surrounding rocks, the larger serpentine bodies are from 450 to 800 feet thick. The serpentines are concentrated in the upper part of the section as are the other Franciscan igneous rocks. Nearly all the extensive bodies have been intruded as sills; those serpentines directly associated with the diabase-gabbro sills are thought to have developed through gravity differentiation. However, other serpentines show no apparent relationship to diabase-gabbro rock, and must have been injected from already differentiated magma. In addition to intrusion as sills, small patches of serpentine have been spread throughout the Franciscan and Knoxville terrane as fault smears; serpentine along faults is commonly altered to silica-carbonate rock.

The serpentine which intrudes Knoxville shale along the ridge northeast of Healdsburg, south of Fitch Mountain, and west of Brooks Creek, appears to have reached its present position by rise as a piercement fold, a type of structure found at a few other localities in the Coast Ranges. The shale immediately adjoining this serpentine shows no alteration whatsoever, and northeast of Healdsburg it further displays the anomaly of dipping into the serpentine from either side. The structure is very complex in this area, but the serpentine appears to be near or on the axis of a tight to overturned anticline in the Knoxville. The readiness with which serpentine smears along faults elsewhere in the quadrangle suggests a plastic mobility sufficient to easily accomplish cold intrusion along the axis of a tight anticline.

The serpentines commonly produce slopes barren of soil, that can be recognized from afar by their bluish-green color. In many cases they show on aerial photographs as light bands covered with a characteristic low brushy overgrowth. In Healdsburg quadrangle, low-growing pungent tarweed is almost confined to serpentine soil, making it possible to "smell out" serpentine exposures before they are seen.

Silica-Carbonate Rock. A variety of curious rock types has been developed by hydrothermal alteration of serpentine. These rocks are composed of various proportions of ferroan dolomite, opal, chalcedony, and quartz; the combination produces a wide color assortment in mottled vitreous to porcellaneous whites, greens, reds, browns, and yellows. Silica-carbonate rock commonly preserves a part of the original sheared serpentine texture, and differential leaching of carbonates by surface weathering leaves a conspicuous mesh-work silica structure. Silica-carbonate rock is ordinarily more resistant than the enclosing serpentine, and stands up as sharp dike-like ledges. It has been described in detail by Knopf,[14] Bailey,[15] and Myers and Everhart.[16]

Silica-carbonate rock is of economic importance, as it forms the gangue for quicksilver minerals in the Great Eastern and Mount Jackson mines near Guerneville and in the Mayacmas quicksilver district, the extreme western edge of which passes through the northeastern corner of Healdsburg quadrangle. It is also of considerable value in tracing faults through the extremely complicated Franciscan rocks, as its presence appears to be ipso facto evidence of faulting.[17]

The time when serpentine was altered to silica-carbonate rock is not known. In part, at least, alteration was concurrent with or prior to deposition of Sonoma sediments, for Sonoma conglomerate exposed along the north branch of Gird Creek contains silica-carbonate pebbles. It is probable that some alteration of serpentine to silica-carbonate rock has accompanied each faulting episode.

Schist. A full suite of Franciscan glaucophane schists is present in the Healdsburg quadrangle. Indeed, the great schist body that forms Big Ridge is one of the largest anywhere in the California Coast Ranges. The many mineral types and assemblages that compose the schists make a generalized description difficult. The common types encountered and sampled are glaucophane-muscovite-quartz schist, some of which contains lawsonite; glaucophane-garnet schist; glaucophane-actinolite schist; actinolite schist; glaucophane-muscovite-omphacite-sphene-garnet schist; and tremolite-clinochlore schist; talc; and amphibolite.

The schists are in general compact, fine-grained and schistose, although massive forms do occur. Elongated crystals, if present, are parallel to schistosity, but may show random orientation within the plane. Nearly all the metamorphics are strongly contorted, sheared, and traversed by innumerable quartz veinlets. The wide variation in mineral composition and the accompanying variation in resistance to weathering within the same schist body produce the knobby topography so characteristic of Franciscan metamorphic terranes.

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[14] Knopf, A., An alteration of Coast Range serpentine: Univ. California Dept. Geol. Sci. Bull., vol. 4, no. 18, pp. 425-430, 1906.

[15] Bailey, E. H., op. cit.

[16] Myers, W. B., and Everhart, D. L., op. cit.

[17] Taliaferro, N. L., Franciscan-Knoxville problem: Am. Assoc. Petroleum Geologists Bull., vol. 27, no. 2, pp. 109-219, 1943.

Schists containing glaucophane are the most conspicuous and abundant. Glaucophane-muscovite-lawsonite-quartz schist, locally graphitic, forms the greater part of the major metamorphic bodies west of Black Mountain and at Big Ridge. In thin section, this schist shows irregular muscovite layers interleaved with narrow quartz bands. Within the muscovite layers, tufts of glaucophane and short lawsonite rods have developed. This type of schist is considered the normal developmental stage between an initial arkose sandstone or shale and a final glaucophane-lawsonite-quartz schist. The small quantity of graphite present is derived from carbonaceous material.

Those schists composed of glaucophane with actinolite, with garnet, or with omphacite, are considered to be derived from greenstones, for the silica content is low. Tremolite-clinochlore rock is in the same category.

Talc schist developed by hydrothermal alteration of serpentine was noted at a single locality in the fault zone along Mill Creek.

Amphibolite, other than glaucophane rock, is rare. A small body is present in the fault zone west of lower Brooks Creek. Microscopic examination shows the chief constituent to be a member of the pargasite-hornblende group; small patches in individual crystals show typical glaucophane pleochroism resulting from the local presence of soda. The amphibolite is the metamorphic equivalent of basic igneous rock.

Many of the schists suffered slight retrogressive metamorphism, in which new mineral adjustment was made to temperatures lower than those that produced initial metamorphism, as evidenced by local chloritization of garnet.

The schist body on Big Ridge is estimated to be 4,000 feet thick; that west of Black Mountain is not less than 2,000 feet thick. Elsewhere throughout the quadrangle are numerous small schist bodies from a few feet to 50 feet or more in thickness. The metamorphics thicken and thin rapidly and disappear by lateral gradation into normal sedimentary or igneous rock.

The bulk of the schist is found in the two large bodies, the one at Big Ridge, and the one west of Black Mountain. Schist is also associated with the serpentine in the low hills west of Rogers School and near the mouth of Porter Creek. Elsewhere, small exposures are common along igneous contacts or as dragged material in fault zones.

The schists have developed from Franciscan sediments and volcanics by pneumatolytic action of emanations yielded by the basic and ultrabasic intrusives. The effects are localized in rocks immediately adjacent to the intrusive bodies. Taliaferro[18] has found the elements most commonly introduced from the magmatic source to be sodium, magnesium, calcium, titanium, and aluminum.

The Franciscan in Healdsburg quadrangle, as elsewhere in the Coast Ranges, is devoid of fossils useful for age determination. Its age may be fixed within narrow limits, however, by its stratigraphic position above rocks equivalent to the lower Kimmeridgian Mariposa slates of the Sierra

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[18] Taliaferro, N. L., Geologic history and structure of the central Coast Ranges: California Div. Mines Bull. 118, pp. 119-163, 1941.

Nevada, and below fossiliferous middle Portlandian Knoxville beds.[19] In the Healdsburg area the base of the Franciscan is not exposed. The contact with the overlying Knoxville is completely obscured by an igneous complex or by faulting; it is probably gradational.

Upper Jurassic

Knoxville Formation

The Knoxville formation in Healdsburg quadrangle is a thick sequence of dark-gray shale and silt, and some sandstone, largely confined to the valley area. Large parts of the formation are buried beneath terrace or alluvial material. In the exposed portions, dark-gray thin-bedded argillaceous shale with silty laminations and interbeds predominates. Fine mica flakes and abundant carbonaceous material are scattered in the shaly matrix.

Gray limestone is present at various horizons as concretions or thin discontinuous ledges, few of which exceed 6 inches in thickness.

Along the north side of the valley of Dry Creek at the extreme west edge of the quadrangle, a coarse arkose sandstone 40 feet thick is interbedded; sandstone is also common as interbeds 1 inch to 4 inches thick.

Narrow zones of radiolarian shale, in which organisms are visible to the naked eye, are present in the Knoxville along the road to The Geysers at Black Mountain; in Grass Valley; just south of the mouth of Dorman Canyon; 1¼ miles southwest of Chalk Hill; and three-quarters of a mile north of the mouth of Porter Creek. Whether or not these occurrences have stratigraphic significance is uncertain. The radiolaria are too poorly preserved for determination.

No complete section is exposed. The Knoxville may be as much as 5,000 feet thick in Healdsburg quadrangle.

Exposures of the Knoxville in Healdsburg quadrangle are almost all in the central low hills. The only exceptions are small patches protected in the synclines of Grass Valley, Grape Canyon, Porter Creek, and a small down-faulted area on the west slope of Black Mountain. To the southeast, the Sonoma volcanics mask any possible continuation of Knoxville; to the east, the nearest exposures are in Pope Valley, approximately 20 miles distant; to the west, no Knoxville is known. It is probable that the Knoxville in the Geyserville syncline extends northwest of the quadrangle boundary, but the area has not been mapped. Preservation of Knoxville in the Healdsburg quadrangle, far from its next nearest exposure, indicates the Geyserville syncline to be of major proportions. Land areas to the west contributed clastics to the sea in which the Knoxville was deposited.

The Knoxville sediments have many features of near-shore marine deposits, such as ripple cross-bedding, intercalated heavy sand bodies, and considerable carbonaceous material, all of which suggest the marine phase of deltaic accumulation. Three fossil localities have been found in the area mapped—(1) at Schoolhouse Creek, (2) at Dutcher Creek, and (3) on the low ridge northeast of Fitch Mountain. A fourth locality is present in a fault zone in Franz Creek about a quarter of a mile east of the quadrangle boundary. The Schoolhouse Creek and Franz Creek localities yielded numerous specimens of *Aucella piochii* Gabb. A single ammonite specimen, *Berriasella storrsi* (Stanton) came from locality three.

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[19] Taliaferro, N. L., Franciscan-Knoxville problem: Am. Assoc. Petroleum Geologists Bull., vol. 27, pp. 109-219, 1943.

The above species are characteristic of the upper Knoxville (Newville group) at its type locality along the west side of the Sacramento Valley [21] and are late Jurassic in age.

Well-preserved Aucellas were obtained from Dutcher Creek; these belong to the species figured by Anderson [22] as *Aucella crassicollis* Keyserling, *Aucella piriformis* Lahusen, and *Aucella indigenalis* Anderson. Their position at Dutcher Creek is several hundred feet below the first conglomerate, the logical position to place the Knoxville-Cretaceous contact. Likewise, their stratigraphic position is close to that of the Schoolhouse Creek fauna from the Knoxville. The writer provisionally considers the Dutcher Creek fauna to be high in the Knoxville. The Knoxville fossil specimens (numbers 39055 and 39056) have been deposited in the Paleontological Collections, Cornell University.

At its type area along the west border of the Sacramento Valley, the Knoxville is 16,000 feet thick. Anderson [23] divided it into three groups, the Newville (4,000 feet), the Grindstone (5,400 feet), and the Elder Creek (6,600 feet). Isolated outcrops of Knoxville at Healdsburg and scattered localities in the central Coast Ranges west of the Great Valley are equivalent to the Newville group, youngest of the three. The very thick Elder Creek and Grindstone groups of the type section have not been recognized. This suggests that the lower Knoxville of the Sacramento Valley and part of the upper Franciscan of the Coast Ranges to the west may be coeval, lower Knoxville representing a deeper marine facies farther removed from the source area to the west.

The igneous suite of basic and ultrabasic eruptives and intrusives is entirely within Franciscan lithology in Healdsburg quadrangle. At localities in the central Coast Ranges, however, Taliaferro has observed intrusions into Knoxville.

Cretaceous

Cretaceous deposits in the Geyserville syncline consist predominantly of massive gray to buff cobble conglomerate, and a few thin interbeds of dark-gray carbonaceous silt, shale, and fine sandstone, 50 to 100 feet thick. The cobbles are well-rounded and range from 2 to 6 inches in diameter; there are a few beds of pea gravel and a few boulders as much as a foot in diameter. The cobbles are biotite granodiorite, light-colored porphyries, dark-gray chert, vein quartz, Franciscan arkose, and Franciscan greenstone. The conglomerate matrix is gray, medium- to coarse-grained muscovitic arkosic sandstone with abundant clay flecks, similar in lithology to Franciscan sandstone.

The conglomerates are extremely massive; bedding is difficult to recognize. Over thicknesses of many hundred feet, no sandstone interbeds are to be found. Very characteristic of the Cretaceous conglomerate is the pervasive shearing which has occurred since deposition. Every cobble is shattered along several planes.

Northwest of Dutcher Creek, the amount of conglomerate rapidly decreases and shale increases—a marked gradation in texture along strike.

The Cretaceous in the Geyserville syncline is 5,000 feet thick. The top, however, is not present. In the Healdsburg quadrangle, the Cretaceous is confined to the Geyserville syncline and the Fitch Mountain area. The nearest exposures east of San Andreas fault are 23 miles southeast of Healdsburg in the mountains west of Napa Valley.

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[21] Anderson, F. M., Knoxville series in the California Mesozoic: Geol. Soc. America Bull., vol. 56, pp. 909-1014, 1945.

[22] Anderson, F. M., Lower Cretaceous deposits in California and Oregon: Geol. Soc. America, Special Paper 16, 1938.

[23] Anderson, F. M., Knoxville series in the California Mesozoic: Geol. Soc. America Bull., vol. 56, pp. 909-1014, 1945.

The great thickness of the conglomerate and coarseness of its constituents indicate local derivation, short haul, and rapid dumping. The presence of considerable granodiorite and porphyry from the old land to the west indicates great enough re-elevation there to furnish coarse clastics. The Franciscan debris may have been derived from the marginal portions of the old land onto which it formerly lapped. Evidence points to accumulation along the margin of a rapidly sinking basin backed by an area undergoing intense erosion.

No fossils were found in the conglomerate series; its age is undetermined. Its tentative assignment to the Cretaceous is based on lithology, and on a distribution generally coincident with underlying Knoxville. A slight difference in strike between the conglomerate and Knoxville exists northwest of Lytton, and an unconformity is indicated. However, general parallelism of the conglomerate and Knoxville throughout the quadrangle suggests that the unconformity is not major here. In view of the known Upper Cretaceous transgressions in the central Coast Ranges, it is probable that the conglomerate is Upper Cretaceous in age.

Tertiary

A formation of probable Tertiary age is preserved along the lower reaches of Little Sulphur Creek in an intricately faulted graben. Its base is just within the northern boundary of the Healdsburg quadrangle, whence it is exposed in fault-bounded wedges northward for at least 5 miles.

Thick-bedded red and gray conglomerate consisting of Franciscan debris predominates in the lower 1,000 feet. Above the conglomerate is well-bedded, gray, ostracodal, argillaceous siltstone with numerous buff limestone lenses and concretions; in it only a few massive conglomerate interbeds are present.

The pebble-and-cobble conglomerate is strongly cross-bedded and poorly sorted. Particles are generally well-rounded, but decidedly flat. The debris is derived from the Franciscan and Knoxville formations and possibly from Cretaceous beds; it consists of arkose sandstone, and shale, and some schist, chert, and greenstone. In the lower part of the formation, the conglomerate stands out in massive ledges known locally as "The Bluffs". Local derivation is shown by the coarse texture of the conglomerate. The presence of red beds and of fresh-water mollusks indicates nonmarine environment, as do the very abundant smooth-shelled ostracods. Some nondescript arenaceous Foraminifera, locally present in the siltstones, are brackish water or marine in origin. The beds were deposited as a piedmont accumulation, into which brackish or marine fingers penetrated. The beds are more indurated and therefore probably older, than the Sonoma volcanics mapped at Healdsburg, and they overlie the Franciscan with major unconformity; therefore they are thought to be Tertiary age. Some 3 miles north of the quadrangle boundary, the basal contact, fault repeated, shows the same relationship to the Franciscan.

No accurate determination of the thickness of the Tertiary beds has been made, but in the southern fault wedge, some 2,500 feet is exposed; however, the top is not present. So far as is known, the Tertiary beds are confined in the Healdsburg area to the narrow graben along Little

Sulphur Creek in which they crop out semi-continuously from the northern boundary of the quadrangle northward at least as far as Big Sulphur Creek, some 5 miles.

The Tertiary beds are locally fossiliferous, but so far no fossils of value for determining age have been found. Numerous specimens of the gastropod genus *Carinifex* were collected from a thin conglomerate bed along Little Sulphur Creek about 2 miles north of the Healdsburg quadrangle (University of California Museum of Paleontology location A-5355). Dr. J. Wyatt Durham, of the University of California, identified the specimens, finding them unlike any described species. The genus, which ranges from Jurassic to Recent, is known so far only from freshwater deposits.

Mr. William Binkley, Superior Oil Company micropaleontologist, found a few arenaceous Foraminifera in a siltstone sample several hundred feet stratigraphically below the gastropod horizon (University of California Museum of Paleontology location A-5344). The Foraminifera are too poorly preserved for determination, but their presence is evidence that the formation locally is of brackish-water or marine origin.

Sonoma Group

The Sonoma group includes a heterogeneous series of lava flows, agglomerates, and tuffs interbedded with nonmarine conglomerate, sandstone, and clay.

The basal member of the Sonoma group in the eastern part of Healdsburg quadrangle is a basalt flow, or series of flows, and intercalated tuff. The basalt is exposed at points along the eastern edge of the quadrangle as far north as Barnes Creek, in the central hills at Adam and Eve Redwoods, and to the southeast, west of Rogers School, along Alexander Valley, at Chiquita, and as an isolated patch west of Dry Creek near Felta School. At the surface, the flows have broken along joint planes to form a bouldery rubble. At a few localities excellent columnar jointing is preserved, and, at Chiquita, pillow structure. The rock has a purplish-black aphanitic groundmass, and scattered feldspar phenocrysts as much as 1 centimeter in length. Some phases contain olivine clumps the size of a hazel nut. Flow layering is indistinct or absent except locally.

In thin section, the basalts show sparse, deeply embayed phenocrysts of labradorite, olivine, and augite scattered through a crystalline ground mass of tiny plagioclase laths, interstitial augite, magnetite wisps, and small amounts of brown glass. The texture is pilotaxitic. The only significant alterations have been the conversion of some olivine to iddingsite and antigorite.

The basalt is from 10 to 30 feet thick over most of the area. Locally, as just west of Adam and Eve Redwoods and west of Alexander Valley, it is as much as 100 feet thick. These areas of exceptional thickness probably represent Pliocene valleys. Southeast of the anticlinal nose near the head of Brooks Creek, the flows increase rapidly in thickness to several hundred feet in the Sonoma Mountains.

By far the most important volcanic constituent of the Sonoma group in the area mapped is pumice tuff. In the southeastern portion of the quadrangle, tuffs 400 to 500 feet thick succeed the basalt flows, and another thick body is present about 1,000 feet above the base of the group. The tuffs are characteristically light gray to white in color and are generally massive; white pumice fragments a half inch to 2 inches in diameter

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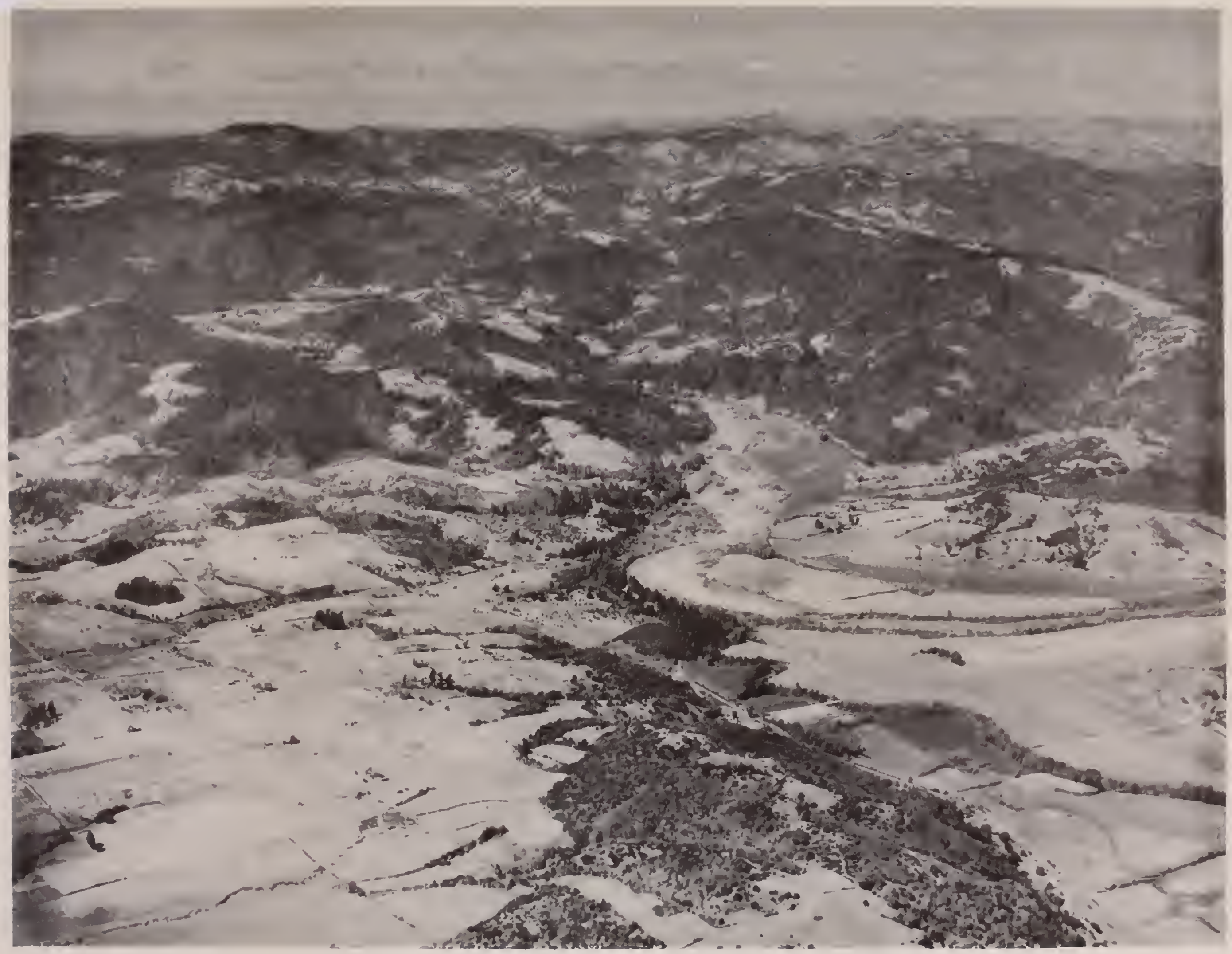

VIEW NORTHWEST IN RUSSIAN RIVER AREA, 8 MILES SOUTH OF HEALDSBURG

The valley of Mark West Creek is in the lower left, with the settlement of Hacienda towards center of photo. The prominent ridge in the upper right is Black Mountain. *Photo courtesy of Clyde Sunderland, Aerial Photographs.*

are abundant at many horizons. A few beds carry scattered breccia fragments of andesite and basalt as large as 6 inches. The tuff is dacitic. Identical tuffs crop out below the Merced formation on the west side of the Windsor syncline; they are 200 feet thick and rest directly on Franciscan. In addition to the tuff bodies, nearly all Sonoma sediments are richly tuffaceous.

A well-developed agglomerate zone is exposed along the low hills west of Alexander Valley in the vicinity of Rogers School.

Layers of welded tuff, pale gray to lavendar in color, are present along the mountain front north of Saysal Canyon and in Miller Creek. Under the microscope they show a few shattered orthoclase and andesine crystals and small xenoliths of olivine basalt enclosed in a groundmass of welded glass shards. The glass has recrystalized and is birefringent. The texture is characteristic of rocks derived by "glowing avalanche" eruptions.

Pale buff poorly consolidated conglomerate and clayey sandstone make up the larger part of the Sonoma group. Thick bodies interbedded with the tuffs, compose the entire ridge immediately east of the Windsor syncline, and overlie the Merced in the west limb of the syncline. They are characteristic river-channel and flood-plain deposits—poorly sorted, strongly cross-bedded and channeled and variable both horizontally and vertically. Conglomerate pebbles range from 1 inch to 6 inches in size, the cobble fractions being very prominent locally. The most common cobbles are of fresh porphyry which was probably erupted shortly before the conglomerate was deposited. Very characteristic of the Sonoma conglomerate are pebbles with a center of jet-black obsidian and thin outer shell of pale-gray friable pumiceous material—apparently produced by water quenching of hot obsidian. In addition to debris from contemporaneous volcanics, a few pebbles of Franciscan red chert and greenstone are present. The matrix is commonly composed of very clayey fine sand with scattered larger grains, and most of it is tuffaceous. The entire rock is friable, and crumbles easily in the hand.

The clastic phase of the Sonoma group is somewhat different in the area southwest of Lytton School and along Gird and Miller Creeks. Here pebble conglomerates are prominent, but in addition, considerable greenish-gray clay is interbedded. On Miller Creek a lignite stratum 1 foot thick is interbedded in the clay.

That alteration of some of the serpentine to silica-carbonate rock took place during or before Sonoma deposition is shown by the presence of a few silica-carbonate pebbles in conglomerate along the north branch of Gird Creek.

In the Healdsburg quadrangle a maximum thickness of 4,000 feet for the Sonoma group as a whole is indicated on the east limb of the Windsor syncline. Clastics account for approximately 3,000 feet; aerial and water-laid pumice tuff and, to a small extent, flow, compose the remainder. However, the volcanic components thicken rapidly to the east and southeast and are the dominant constituent in the Sonoma Mountains. Rapid thinning of the group takes place westward. It is estimated that a diminution by one half occurs across the Windsor syncline.

Exposures in the area mapped represent the most northwesterly edge of the Sonoma group terrane. To the southeast, the volcanic rocks compose a very important part of both the Sonoma Mountains and the

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Exposures in the area mapped represent the most northwesterly edge of the Sonoma group terrane. To the southeast, the volcanic rocks compose a very important part of both the Sonoma Mountains and the southern Mayacmas Mountains. In addition, thick flows are present capping the crest of the Mayacmas Mountains east and northeast of Healdsburg at elevations of 4,344 feet on Mount St. Helena and 4,722 on Cobb Mountain. No rocks of the Sonoma group are found in the mountains west of Dry Creek, with the exception of the exposure mapped at Felta School. However, the marine Merced sandstone, equivalent to a part of the Sonoma, is widely though thinly distributed over much of the western half of the next quadrangle to the south. The areas of Merced mapped in the extreme south-central portion of the Healdsburg quadrangle represent the most northerly extent known.

Narrow belts of Sonoma extending northwest far up Alexander Valley and Dry Creek Valley have been preserved through favorable structural position. Their presence has been influential in the development of the present subsequent drainage.

The source area for both sediments and volcanic rocks was nearby, to the east and southeast. The volcanic rocks are of central cone type and it may be assumed that high volcanos were scattered over the immediately adjoining area. As evidenced by the great predominance of volcanic cobbles in the Sonoma clastic phase, the volcanos themselves became the dominant source for contemporaneous river deposits. Interwedging of the marine Merced formation near the base of the group shows the existence of the strand line within the present area of the Windsor syncline.

The sequence of deposition of the Sonoma group is considered to have been as follows: (1) Volcanic activity was initiated immediately to the east and southeast of Healdsburg quadrangle; the first flows ran far westward along the valleys and blanketed the areas peripheral to cones; (2) activity became largely pyroclastic, contributing thick tuffs and agglomerate; (3) simultaneously, streams consequent on the volcanic slopes attacked the new-made rock, dumping vast volumes of conglomerate as a narrow alluvial apron between the volcanic peaks and the sea.

Interwedging of the fossiliferous marine Merced formation into the lower Sonoma group dates the latter as late Pliocene. In the vicinity of Santa Rosa, shallow marine Sonoma tuffs contain molds of Merced mollusks. No data are available for assigning an exact upper limit to Sonoma deposition.

Sonoma rocks overlie the faulted, folded, and extensively eroded Mesozoic rocks of the Healdsburg quadrangle with profound discordance. The relationship of the Sonoma group to Quaternary terraces is unconformable; the terraces form platforms across the tilted edges of Sonoma strata.

Merced Formation

The limited exposures of Merced formation in the Healdsburg quadrangle are a light-gray, massive to thick-bedded, uniformly medium-grained sandstone that weathers pale buff. It is not cemented, but is soft and friable. Abundant marine mollusk molds are present locally. At Wilson Grove, a fauna beautifully preserved as original material has been collected and described by Dickerson.[24]

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[24] Dickerson, R. E., Tertiary and Quaternary history of the Petaluma, Point Reyes, and Santa Rosa quadrangles: California Acad. Sci. Proc., vol. 11, pp. 527-601, 1922.

The Merced formation grades upward into nonmarine Sonoma sands and gravels and the contact has not been precisely located. A minimum thickness of 500 feet is estimated for the Wilson Grove area. An average thickness of 600 to 800 feet has been reported by Johnson[25] in the Sebastopol quadrangle, adjoining to the south, where the Merced is widely distributed. The Merced blankets the Franciscan terrane west of Llano de Santa Rosa south of the Russian River, and is preserved in structural lows along the San Andreas rift at various points southward to the Golden Gate; it crops out widely southwest of San Francisco, at its type locality. In the Healdsburg quadrangle and adjacent areas to the south, its eastern extent has been controlled by the western flanks of the coeval Sonoma volcanos. The Merced is a beach and shallow marine sandstone containing a littoral molluscan assemblage. Source for much of its sediment must have been the volcanic ranges immediately to the east. Additional clastic rocks may have been derived from a low Franciscan area to the north.

In the Wilson Grove area, Merced strata conformably overlie 200 feet of Sonoma tuff. They are in turn overlain conformably by Sonoma sandstone and conglomerate. The Merced is here a marine wedge interbedded with the Sonoma group. The Merced exposure northeast of Rio Dell overlies the Franciscan with profound unconformity.

Until recently, the Merced formation has been considered middle Pliocene, on the basis of its marine molluscan fauna. Stirton,[26] however, in a study of vertebrate fossils from the San Francisco Bay region, concluded that the horse tooth *Neohipparion gidleyi* Merriam from the Petaluma formation could be no older than late middle or early upper Pliocene. At Petaluma, the Petaluma formation underlies the Sonoma group with marked angular unconformity. It is probable, therefore, that the Sonoma and Merced cannot be older than upper Pliocene. The precise dating must wait upon correlation of vertebrate and invertebrate faunas.

Quaternary

Fanglomerate

Limited exposures of sharpstone conglomerate are present at the south end of Alexander Valley, immediately adjacent to the front of Mayacmas Mountains. The conglomerate consists entirely of angular Franciscan sandstone and greenstone fragments. It is considered to be a remnant of a fanglomerate apron developed during uplift of the Mayacmas Mountains during the Pleistocene. Exposures are too poor to permit an accurate thickness determination, but 50 feet seems a reasonable minimum estimate.

Terraces

Five well-defined terrace levels are recognizable along the valleys of Russian River and Dry Creek. The highest stands between 200 and 225 feet above present river level. This is preserved as a notch in the spur just northeast of Guerneville, as an extensive platform cut across Franciscan greenstone 1 mile southwest of Wilson Grove, at scattered localities along the west side of Dry Creek Valley, as a great fill north of Manzanita School, within the bend of the Russian River north of Fitch Mountain, and as a tilted erosion surface in section 16 east of Maacama Creek. Holway [27] noted the preservation of a stream channel on the top of the hill immediately east of Maacama School, exposed cleanly by a landslide in 1906. This belongs to the same erosion surface. The 200-foot terrace, with the exception of the area north of Manzanita School, is a cut terrace. North of Manzanita School it is fill.

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[25] Johnson, F. A., Petaluma region: California Div. Mines Bull. 118, pp. 622-627, 1943.

[26] Stirton, R. A., Cenozoic mammal remains from the San Francisco Bay region: Univ. California, Dept. Geol. Sci. Bull., vol. 24, pp. 339-410, 1939.

The next lower level stands about 125 feet above present drainage. This is particularly prominent along the east side of Dry Creek and north of Fitch Mountain. It extends as alluvial fans at increased gradient up the larger valleys cut into the central hills east of Dry Creek.

A 75-foot level is preserved in small patches along Dry Creek, north of Fitch Mountain, and at the mouth of Maacama Creek. A level 40 to 50 feet above drainage is present west of the lower Russian River, immediately northwest of Healdsburg, and north of Fitch Mountain.

The remarkably complete series of terraces shown within the bend of the Russian River north of Fitch Mountain owes its preservation to the fact that there the Russian River has continuously migrated northwestward. The interior of the loop has acted as a permanent slip-off slope.

The terrace fill consists of poorly consolidated cross-bedded quartzose sands, gravels, and conglomerates, the pebbles of which are predominantly Franciscan, Knoxville, and Cretaceous sandstone and shale, with lesser amounts of the other Franciscan varieties, and locally Sonoma debris. These pebbles may be as large as 4 inches in diameter. Sediments of the 225- and 125-foot terraces have weathered red; the younger deposits are still buff colored.

Alluvium

The broad flat alluvial areas which form the floors of Dry Creek Valley, Alexander Valley, and the Russian River canyon represent the most recent interval of relatively long stability in the drainage system. This level extends far up the tributary valleys; it forms the floor of the abandoned meander of Guerneville. Aerial photographs show clearly the countless migrations of the meander belts across the broad tracts. In years of extraordinarily heavy rainfill, Alexander Valley and the valley below Healdsburg are still subject to floods. A rancher living at the point of the bend northeast of Healdsburg recorded a rise of 30 feet above normal there December 11, 1937, the flood waters having backed up at the Fitch Mountain narrows. The same flood rose 23 feet at a point in Alexander Valley about 1 mile southwest of Jimtown. On February 28, 1940, a high of 22 feet was measured.

However, this alluvial surface has already been incised 15 to 20 feet in the canyon of the Russian River, and is itself on the way to becoming yet another terrace level, for the Russian River, has very recently become once again an actively downcutting stream. Holway [28] noted that a dense redwood forest originally covered the abandoned meander floor at Guerneville. Some cut redwoods showed 2,400 annual rings, and below one such stump was a prostrate buried redwood of large size. He estimates that abandonment of the meander took place about 5,000 years ago and a similar age may, therefore, be assigned to the peak of development of the broad alluvial surface.

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[27] Holway, R. S., The Russian River, a characteristic stream of the California Coast Ranges: Univ. California, Pub. Geography, vol. 1, no. 1, pp. 1-60, 1913.

[28] Holway, R. S., op. cit.

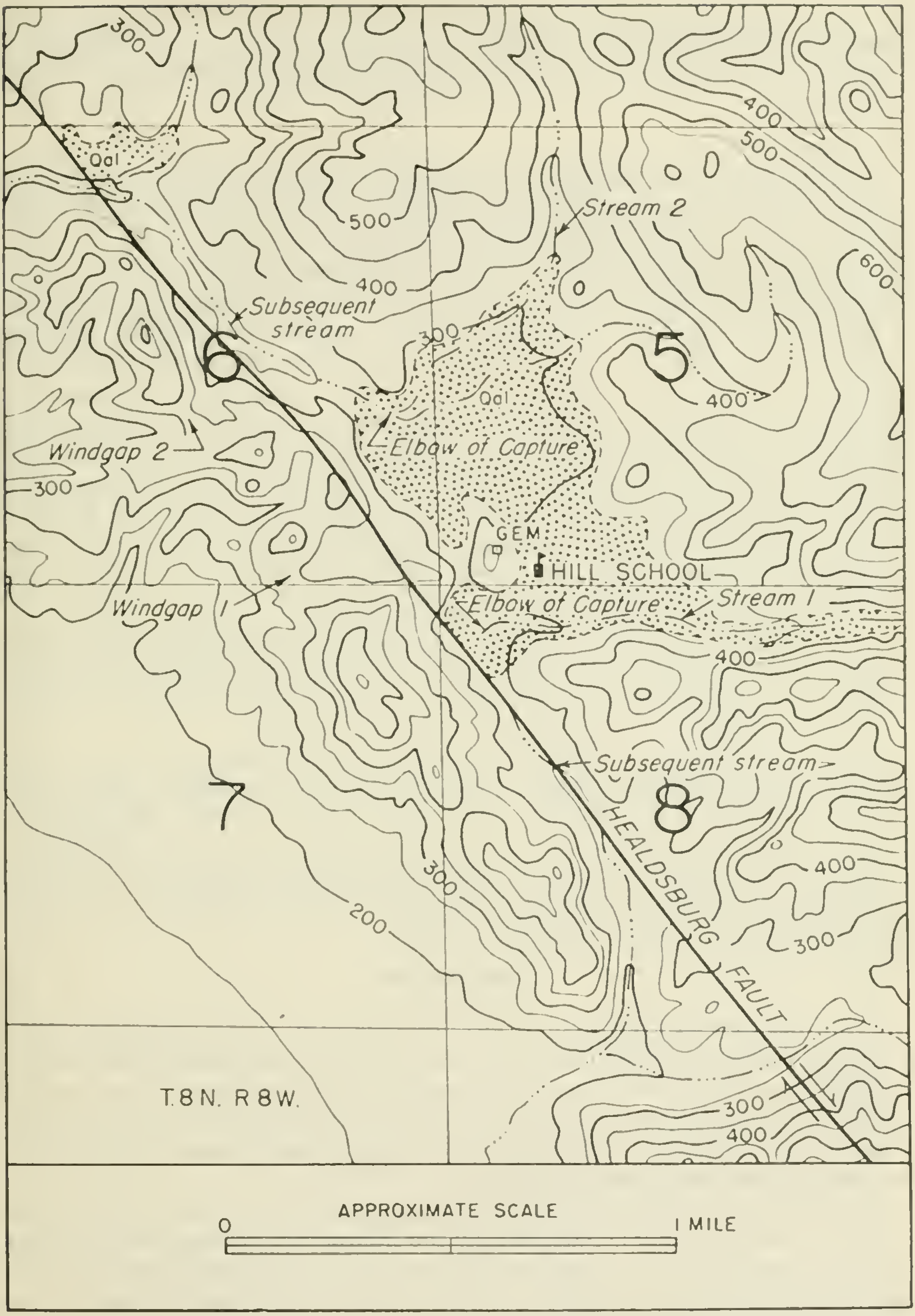

FIGURE 3. The Hill school area, 6 miles southeast of Healdsburg, showing perched alluvium (Qal), and other physiographic features

The alluvial areas mapped along the east side of the Windsor syncline and in the hollow northeast of Healdsburg are thin veneers of material derived from the adjacent slope and spread out as a wide apron at its foot.

Landslides

A combined area of many square miles in the Healdsburg quadrangle is covered by large-scale slides. Recognition of slide areas is of utmost importance for accurate geological mapping, but in the case of older slides this is not easy. Younger slides show their origin by their tongue-like extension down valleys or a distinct down-slope lobate form, as well as by presence of the lunate scar from which they plunged. In older slides, the scar may be gone, the lower edges straightened. However, a hummocky surface, a jumbled variety of rock types, ground-water seepage, and a profusion of small parallel gullies as consequent drainage, are strongly indicative of landsliding. It has been noted on several valley-filling slides that consequent streams develop between the slide materials and the old valley wall on both sides. These join at the slide end. Presumably, as erosion proceeds to clear away the slide material, the two streams gradually approach each other, finally merging into a single stream flowing down the center of the cleaned-out valley.

The rocks most liable to slide are those most strongly sheared—the rocks in and adjacent to fault zones. When these sheared rocks are located on oversteepened slopes, as is the case along the front of the Mayacmas Mountains, large-scale sliding is assured.

The numerous earthquakes which have affected the California coastal regions have served as triggers to start the slides plummeting down slope. Lawson [29] noted innumerable slides developed in areas near the San Andreas fault as an aftermath of the 1906 earthquake. In the Healdsburg quadrangle, the small slide at Maacama School is of that date. Maacama Creek was impounded to form a small lake which lasted the few days necessary to build up and breach the dam.

STRUCTURE

The structural complexity characteristic of the Healdsburg quadrangle has arisen from at least four superposed diastrophic events. Difference in trend between earlier and later deformations is responsible for almost complete loss of identity of early structures. Much structural development occurred during the long depositional break in early Tertiary and cannot be precisely dated.

The gross structural relationships now shown are (1) anti-clinorial areas of Franciscan rock composing the Mayacmas Mountains and Mendocino Range, and (2) a major syncline between them in which Knoxville and Cretaceous formations are preserved. Superposed indifferently across the earlier structural trends is the Windsor syncline in Pliocene rocks. The whole has been intricately fragmented by a northwest-trending system of distributive normal and strike-slip faults.

Folds

The notable feature of folding at Healdsburg is its general open symmetrical nature. Overturning is developed locally, but overfolding and thrusting are fairly small scale. Two periods of folding are clearly represented: (1) post—Upper Cretaceous, and (2) post deposition of the Pliocene Sonoma group. A third period is probable between the close of the Jurassic and Upper Cretaceous.

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[29] Lawson, A. C., Branner, J. C., Gilbert, G. K., Reid, H. F., and others, The California earthquake of April 18, 1906: Carnegie Inst. Washington Pub. 87, pp. 1-451, 1908.

Pre-Upper Cretaceous Warping. Warping after deposition of the Knoxville, but pre-Upper Cretaceous, is suggested by apparent slight differences in strike between the Knoxville and Cretaceous beds along the west side of the Geyserville syncline northwest of Lytton. The contact itself, however, was nowhere seen, so the indicated unconformity may not be actual. If an unconformity is present, it must be small, for the Knoxville formation and Upper Cretaceous deposits are roughly coextensive throughout the area.

Post-Upper Cretaceous Warping. The conspicuous folding which has affected the Mesozoic rocks can be dated no more accurately than later Upper Cretaceous and earlier than deposition of the Sonoma group. This orogeny produced the large-scale folds represented by the ill-defined anticline south of Black Mountain, the Geyserville syncline, the irregularly synclinal area at Bradford Mountain, the Mill Creek anticline, a synclinal area at Porter Creek, and an undulating, generally anticlinal structure at Guerneville. Anticlinal areas, largely destroyed by subsequent faulting, are inferred below the alluvium on either side of the Geyserville syncline; the Knoxville exposures north of Fitch Mountain and the Franciscan area west of Rogers School are exposed portions of these.

Save for a part of the Geyserville syncline, later faulting has fragmented the structures, nearly obliterating the anticline south of Black Mountain.

Folding was on a large scale, but did not reach an intensity great enough for overturning and thrusting. As judged by present dips, which have doubtless been locally increased by deformation that occurred after deposition of the Sonoma group, the inclination on fold limbs varied from 20° to 60°. The areas of steeply dipping to overturned beds characteristic of Fitch Mountain and vicinity are to be attributed to later faulting and post-Sonoma compression. Average fold trend is N. 70° W. from 20° to 25° more to the west than the trend of later faulting. This difference in trend accounts in large measure for present structural complexity, for the faults have cut the earlier folds obliquely. As an example, the southeastern end of the Geyserville syncline is truncated by the fault zone in the Russian River loop; its southeasterly continuation has not been found, unless the Knoxville fault smear east of the quadrangle boundary along Franz Creek is related.

The axial trend of the Geyserville syncline is anomalous between Canyon School and Lytton. Neither the southern portion, which bears N. 45° W., nor the northern portion, which swings south of west, conforms to regional strike. This is the result of heterogeneous folding. The igneous rocks of Bradford Mountain are locally thickened, and their superior resistance to folding has prevented normal shortening. As a result the adjoining weaker rocks were forced to wrap around them. The anomalous trend of the Geyserville syncline thus conforms to the outline of the locally overthickened igneous mass. The Franciscan sediments south of Bradford Mountain have been similarly affected and bulge toward the south. Dips along the west limb of the Geyserville syncline steepen progressively toward the area of minimum shortening in the Bradford Mountain igneous complex.

As now exposed, the thickest portion of the igneous mass is not directly opposed to the maximum bow in the Geyserville syncline. At the time of folding, however, it lay about 3 miles more southeast relative to the Geyserville syncline, having reached its present position by strike-slip movement on the Healdsburg fault.

Plate 4 is a compilation showing post-Jurassic diastrophism for the central Coast Ranges, San Francisco Bay, and northern Coast Ranges. Data for the northern Coast Ranges are scanty, for most of the Tertiary is absent. As Taliaferro [30] points out, the Coast Ranges have been characterized by localized basins since the Eocene. Fragmentation of the extensive Upper Jurassic-Lower Cretaceous geosyncline began as early as the mid-Cretaceous disturbance. With local basins of deposition and areas of emergence, regional correlations of diastrophic events are difficult, for a gradational contact in one area may be a disconformity or angular unconformity close by. Therefore, those events which appear insignificant in the central Coast Ranges and San Francisco area may have been important in the interior of the northern Coast Ranges. Taliaferro has observed that, in general, the intensity of post-Jurassic diastrophisms consistently increases westward from the Great Valley.

Nevertheless, plate 4 shows a general parallelism between events in the central and northern Coast Ranges. The most important deformations between Upper Cretaceous and late Pliocene appear to be the Santa Lucian orogeny in mid-Upper Cretaceous, an Eocene-Oligocene interval of folding and large-scale normal faulting not precisely dated, folding and uplift between middle and upper Miocene, and an orogenic episode between middle and upper Pliocene.

At Healdsburg, Franciscan, Knoxville, and Upper Cretaceous(?) rocks are folded, trending approximately N. 70° W. The structures were subsequently cut by more northerly large-scale normal faults. Between the folding and faulting episodes, the undated formation along Little Sulphur Creek was deposited. Since neither the age of the Upper Cretaceous(?) in the Geyserville syncline nor that of the beds along Little Sulphur Creek is known positively, dating of the folding and faulting episodes is impossible.

A probable lower time limit for the folding may be deduced by reference to the Covelo, Clear Lake, and San Francisco Bay areas. Where Paleocene deposits are present, they unconformably overlie Upper Cretaceous deposits. This general relationship indicates that the unconformity is not of great magnitude, for erosion was limited. Field evidence confirms this.[31] The relationship of the Paleocene beds to lower or middle Eocene beds is also unconformable. Here again, however, both areal distribution and local field evidence indicate that the diastrophism was probably too small to account for the major folding at Healdsburg. Dickerson's map of the Upper Cretaceous, Paleocene, and middle Eocene formations at Clear Lake shows this group to be preserved in a syncline that trends N. 70° W., the same as the folding at Healdsburg.

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[30] Taliaferro, N. L., Geologic history and structure of the central Coast Ranges, California: California Div. Mines Bull. 118, pp. 119-163, 1941.

[31] Dickerson, R. E., Fauna of the Martinez Eocene of California: Univ. California, Dept. Geol. Sci. Bull., vol. 8, no. 6, pp. 61-180, 1914.

It therefore seems reasonable to assign the folding at Healdsburg to post-middle Eocene, pre-middle Miocene. If this conclusion is valid, it indicates a like age for the deformation which Taliaferro[32] placed in the post-Paleocene pre-Miocene interval. Widespread deformation at this time might well explain the very limited distribution of Oligocene sediment in the California Coast Ranges.

Folding After Deposition of Sonoma Group. Gentle folding succeeded deposition of the Sonoma group and Merced formation. Small synclines and anticlines were formed in the Brooks Creek area, and a narrow syncline under Alexander Valley and Dry Creek Valley. Inclinations rarely exceeded 10°, although many are now 30° to 90° in the immediate vicinity of the major faults. More representative of this gentle folding is the area of Merced mapped by Johnson[33] to the south. There, west of Llano de Santa Rosa, the Merced formation is little disturbed by faulting and has a maximum dip of about 10°.

Oblique faulting subsequently affected the well-defined folds in the Brooks Creek area, so that their exact trend is difficult to determine. General trend of the anticline northeast of Hill School is N. 40° W.; of the syncline between Brooks and Franz Creeks, N. 50°-60° W.

The folding is tentatively dated as lower Pleistocene and is considered a phase of the major Coast Ranges orogeny.

Steepening of the dip of the Sonoma beds after gentle folding is ascribed to drag accompanying subsequent normal faulting, and to renewed but localized compression attendant upon large-scale strike-slip faulting. For instance, considerable steepening by drag is found along the Maacama zone of normal faulting. Steep to overturned dips are present in the Sonoma beds along the Maacama zone, vertical dips along the Healdsburg zone, and 65° dips within the Alexander zone.

Windsor Syncline. Structure of the Sonoma-Merced formations underlying Llano de Santa Rosa is generally synclinal, but is not regarded as a compressional downfold. These rocks were deposited on an old erosion surface which was subsequently upwarped to the north to form the present Mendocino Range. At Healdsburg, the erosion surface plunges rapidly southeast, passing under the Windsor syncline to below sea level. As judged by the shallow marine aspect of the Merced formation and the continental character of the Sonoma group, the present elevation of these rocks is not radically different from that at which they were deposited. The elevation of the erosion surface has here remained relatively stable. However, Sonoma beds are lower than the marine Merced to the west, indicating a marked southeast tilting. During this tilting the Sonoma rock, which now underlies Llano de Santa Rosa, rode passively down to its present position. The inclination of the western side of the Windsor syncline is, then, the inclination imparted by southeast-plunging tilt of the Mendocino Plateau. The eastern side is delimited by the faulted front of the greatly uplifted Mayacmas Mountains. During the compression accompanying strike-slip faulting, the east side of the structure was folded up to its present position to produce a synclinal area. Fundamentally, though, the syncline is no more than the low point on the tilted Mendocino Plateau block.

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[32] Taliaferro, N., Geologic history and structure of the central Coast Ranges, California: California Div. Mines Bull. 118, pp. 119-163, 1941.

[33] Johnson, F. A., Petaluma region: California Div. Mines Bull. 118, pp. 622-627, 1943.

Faults

The outstanding structural feature at Healdsburg is the intricate fault system, the dominant control of present topography and drainage. The west front of the Mayacmas Range is directly molded by faulting; its oversteepened slope is the eroded Maacama zone, and its relative elevation is fault displacement. Fault-controlled distribution of the weaker rock has had still greater indirect influence on topography. Along the less resistant belts so localized, major subsequent streams rapidly developed which now dominate the drainage. Both Dry Creek and Alexander Valley are of this origin. Further, the crushing in the fault zones themselves, even in resistant rock, has made easy the growth of subsequent drainage. Dutcher, Wallace, Peaches, and Hobson Creeks are so formed. The sinuous course of the Russian River between Alexander Valley and Healdsburg is a striking example.

Characteristic features along the latest faults are the perched alluviated valleys. Impounding of drainage at new fault scarps has formed ponds in which alluvium has been deposited until through drainage is again established—a long process under the semiarid conditions at Healdsburg. Such drainage may be resumed through the old channel, but in many cases it is captured by a subsequent stream working rapidly along the fault zone. A remarkable example of the latter is seen in the perched alluvial area at Hill School. Here a relative movement of the southwest side up and to the northwest along the Healdsburg fault beheaded two small creeks. The gap in the ridge west of Gem is the beheaded valley of the creek just south of Hill School; the gap half a mile northwest is the valley of the creek north of Hill School. The upper reaches of each creek have been captured by subsequent streams. The small perched alluvial area in the northwest corner of section 6 shows fault damming of a stream that later was able to re-occupy its original channel. Other perched alluvial areas are present along the front of the Mayacmas Mountains between Saysal and Gird Creeks, at the head of Miller Creek, east of Chianti, and at Chiquita. Both examples east of Chianti show piracy. Where present, perched alluvium is an easily recognized criterion of recent faulting.

The fault zones are marked by alignment of straight drainage segments, by oversteepened slopes, nicked spurs, aligned knobs, landslides, sag ponds, seepage, aligned serpentine smears, and linear occurrence of silica-carbonate rock. Those faults with wide gouge zones of serpentine and schist may support only grass, which shows as a conspicuous light-colored band on air photos. Many of these features are well illustrated by photographs along the San Andreas fault published in the California Earthquake Commission report.[34]

Three periods of major faulting are recognizable: normal faulting, exemplified by the Little Sulphur graben, which took place prior to deposition of the Sonoma group; dip-slip faulting along the Maacama zone, which took place after deposition of the Sonoma group; and still later strike-slip faulting, most perfectly shown by the Healdsburg zone. Strike-slip movement in the latest episode took place along both new and pre-existing faults.

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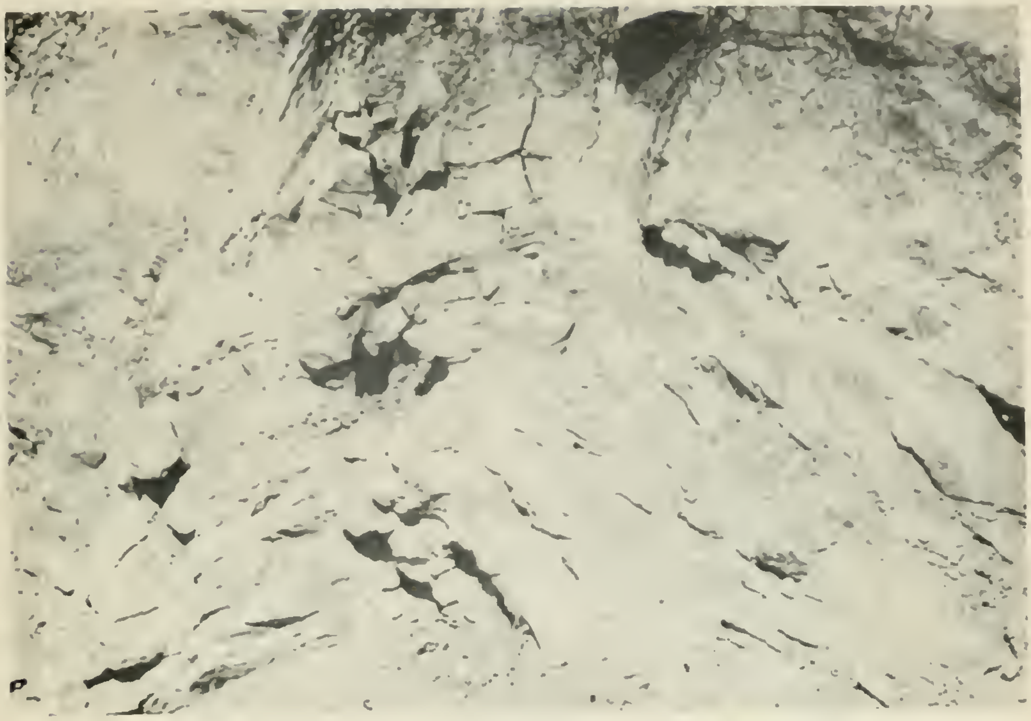
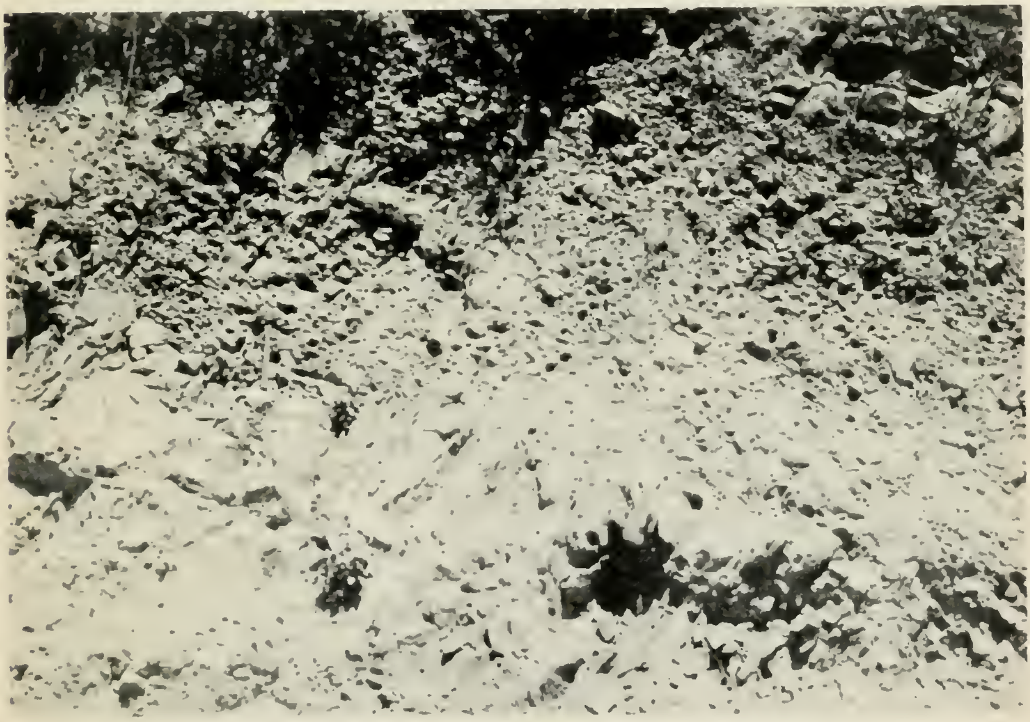
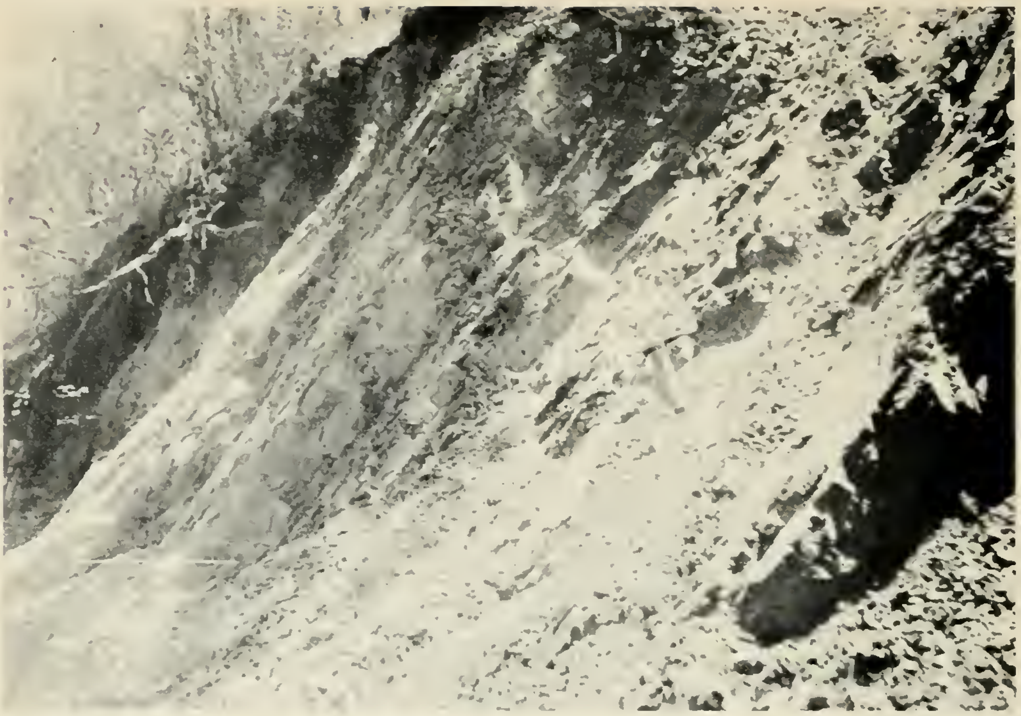
[34] Lawson, A. C., Branner, J. C., Gilbert, G. K., Reid, H. F., and others, The California earthquake of April 18, 1906: Carnegie Inst. Washington Pub. 87, pp. 1-451, 1908.



A, SMALL ANTICLINE IN THICK-BEDDED FRANCISCAN SANDSTONE.
Thin shale partings separate the thick sandstone beds. Height of exposure is about 20 feet. Lower Saysal Creek.



B, CRETACEOUS (?) COBBLE CONGLOMERATE WITH ARKOSE SANDSTONE LENSES.
Geyserville syncline 1 mile southwest of Geyserville.



A, CRETACEOUS (?) SHALE AND SILTSTONE BODY INTERBEDDED IN CONGLOMERATE.
One mile southwest of Geyserville.

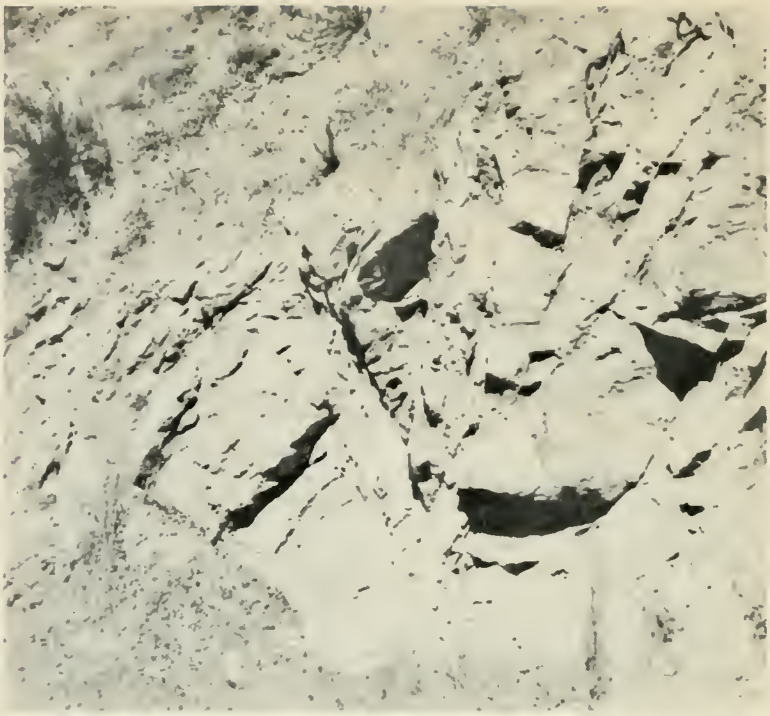
B, VIEW NORTH ALONG RIDGE TOP WEST OF LITTLE SULPHUR CREEK.
The Little Sulphur fault runs straight up the center of the picture, separating Franciscan on the left from massive Tertiary (?) conglomerate on the right.

A, SOUTH FACE OF BLACK MOUNTAIN SHOWING LANDSLIDE SCAR.

Grassy slope in middle ground is old slide exhibiting typical hummocky surface and seepage.

B, CLOSEUP OF FRANCISCAN-TERTIARY (?) FAULT CONTACT ALONG LITTLE SULPHUR FAULT.

Light soil on left is serpentine, the knobs, schist. The down-faulted conglomerate beds lie on the right. Note drag effects.



SHALE LAYERS SQUEEZED INTO SHEAR SETS IN MASSIVE FRANCISCAN SANDSTONE.

A difference in trend is distinguishable between earlier and later major faults, but such difference is largely obscured in the Healdsburg quadrangle by the dominating strike-slip trend. The faults are all considered to be high angle. In the field, the zones are too wide and the exposures too poor for accurate dip determination. On air photos, however, they are seen to strike across rugged topography with but minor deflection between mountain and valley. Detailed subsurface mapping in the Mount Jackson-Great Eastern mine near Guerneville indicates that the bounding surfaces of the Mount Jackson fault are steep; the main mineralization has taken place along a subsidiary fault dipping 80° N.[35] Subsurface maps of quicksilver mines in the western Mayacmas district, which lies immediately northeast of the Healdsburg quadrangle, show the major faults commonly inclined 60° to 85°, some to the east, some to the west.[36] The writer is therefore confident that faults in the Healdsburg area are high angle, and that 70° to 90° dips predominate. Since accurate dip data are lacking, the faults have been arbitrarily drawn as vertical on cross-sections.

Along Little Sulphur Creek, Tertiary (?) conglomerate is faulted into Franciscan as a graben between the Little Sulphur and Black Mountain fault zones. A minimum dip-slip movement of 2,800 feet is obtained by comparing the elevations of the Tertiary (?) base and immediately adjoining Franciscan just north of the quadrangle boundary. As the distribution of Tertiary (?) outside the graben is not known, no accurate measurement is possible. Only the southernmost tip of the Tertiary (?) lies within the Healdsburg quadrangle.

The Little Sulphur fault line is exposed along the ridge crest west of Little Sulphur Creek. Drag effects in the Tertiary (?) are localized in the immediate vicinity of the fault. Within less than 100 feet, the conglomerate steepens from a regular dip of 18° to vertical, and the strike swings some 70° until parallel to the fault trend. The conglomerate is very little shattered here, probably because it is faulted against serpentine, which served as a lubricant. Farther southeast, at Miller Creek, two parallel faults appear to the northeast, and the combined zone is traceable across Saysal Canyon, to become lost in the greenstone.

The Black Mountain zone is extremely complicated, particularly where it becomes profusely branched west of Black Mountain. It determines the southwest edge of the Black Mountain greenstones. To the southeast it is hidden for more than a mile by a great landslide, but its continuation beyond is traceable to the quadrangle boundary.

Uncertainty as to stratigraphic position within the Franciscan formation makes it impossible to recognize the graben south of the Tertiary (?) outcrop. The basin drained by Saysal Creek coincides with it in a general way.

Northwestward, both faults may be traced by aligned subsequent streams and knobbed spurs across the adjoining sheets. They determine the 4-mile S. 45° W. segment of the Russian River valley immediately below Hopland, cross to the west side of the river at that town, and continue up Feliz Creek valley to Crittendon.

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[35] Myers, W. B., and Everhart, D. L., Quicksilver deposits of the Guerneville district, Sonoma County, California: California Jour. Mines and Geology, vol. 44, no. 3, pp. 253-277, 1948.

[36] Bailey, E. H., op cit.

A second area of dip-slip faulting includes the Geyserville syncline and Fitch Mountain. The greater part of the bounding faults are probably buried beneath the alluvium of Dry Creek and Alexander Valley. Where they are exposed, subsequent movements on the same zones have greatly confused the earlier episode. The east side of the graben is represented in the extremely complicated Franciscan-Knoxville-Cretaceous area west of Rogers School. Here the south end of the Geyserville syncline is dropped along the Alexander fault zone against Franciscan. The northward continuation is buried for 3 miles. It follows the west side of Alexander Valley, determining the straight east edge of the Geyserville syncline near Geyserville, and reappears as the fault pair west of Chianti along which Cretaceous and Knoxville have been downfaulted against Franciscan.

The fault zone bounding the west side of the graben is even more obscure because of extensive cover. The Fitch Mountain fault, along which Cretaceous is dropped against Knoxville, may represent it, or may be but a cross fault. The Dry Creek fault is considered a part of the zone, for along it, just west of the quadrangle boundary, Knoxville is in fault contact with Franciscan. Between these two areas, the zone is buried by the terraces and alluvium along Dry Creek.

In both sides of the graben, Cretaceous and Knoxville strata involved in the faulting stand at high angles or are overturned. While some steepening must have accompanied the forming of the graben, much more may be attributed to folding and compression attendant on strike-slip adjustments. These later deformations make accurate calculation of original movement impossible. Both bounding zones, however, indicate stratigraphic throws roughly equivalent to the thickness of the Knoxville, about 4,000 feet.

The Alexander fault zone, on topographic evidence, appears to continue southeastward and may control the east side of Kenwood Valley. A few miles northwest of the quadrangle boundary, it is joined by the Healdsburg strike-slip zone; the combined zone is traceable diagonally across the adjoining quadrangle, crossing the Boonville road between Yorkville Post Office and Ingram. The poorly defined west side bounding zone cannot be traced.

The larger portion of these dip-slip faults are hidden by alluvium, or masked by the more recent N. 45° W. strike-slip system. There is, nevertheless, indication that the trend may have been more westerly than N. 45° W., for the Fitch Mountain and northwest Dry Creek Valley segments are oriented nearly due east.

The normal faulting is earlier than late Pliocene, for Sonoma rocks are not affected. If inferences regarding the time of folding of Upper Cretaceous (?) and older rock be valid, then the faulting is post-middle Eocene. A comparison with the time of known major normal faulting in the central Coast Ranges suggests that it falls within the middle Eocene to Miocene interval. However, no evidence precludes a later date for the faulting, and during both the Miocene and early Pliocene there was strong diastrophic activity in the San Francisco area.

The Maacama and Chianti fault zones determine the structural boundary between the Mendocino Plateau and Mayacmas Mountains in the Healdsburg area. Along these zones, dip-slip movements distributed among many parallel faults have brought Sonoma volcanics against the

Franciscan formation east of Alexander Valley. As Sonoma rocks have been removed from that part of the Mayacmas range immediately to the northeast of the fault zones, only minimum movements may be calculated. At Maacama Creek, Sonoma beds have been relatively dropped at least 1,300 feet; at the head of Miller Creek they have been dropped at least 2,100 feet, if it be assumed that Black Mountain was once covered by the Sonoma. Along the Chianti zone of Miller Creek, a 500-foot displacement is indicated. The Mayacmas Mountains were uplifted relative to the Mendocino Plateau; the oversteepened front east of Alexander Valley is the greatly eroded multiple fault scarp.

On topographic maps, the Maacama fault zone may be traced southeastward from the Healdsburg quadrangle for about 7 miles. It appears to continue beyond this point almost straight, to the west of Mount Hood. This may well be the fault shown on the geologic map of California [37] passing down the Mayacmas Mountains crest, and out along Carneros Creek; it can be projected directly into the Concord fault. North of the quadrangle, the east pair of faults join the Little Sulphur fault, the combined zone being traceable to Crittendon.

The Chianti zone is indicated by topographic evidence to continue northwestward at least 9 miles. It controls a short N. 40° W.-trending segment near the mouth of Big Sulphur Creek and is probably responsible for Preston Lake. It has not been identified south of Alexander Valley.

This system shows a consistent bearing of N. 40° W., the same as later strike-slip faulting. Indeed, it is thought that subsequent strike-slip movements have occurred along most of these faults; the perched alluvium east of Chianti is definite evidence of such.

The period of block faulting along the Chianti and Maacama zones is correlated with the diastrophism [38] in which the Berkeley Hills and Marin blocks were uplifted. In the Healdsburg area it accompanies uplift of the Mendocino Plateau and Mayacmas Mountains to near their present elevation. It may well be coincident with the middle Pleistocene orogeny which strongly affected the central and southern Coast Ranges.

An intricate system of strike-slip faults and accompanying secondary shears has been superimposed on all older deformations. This system has controlled much of the subsequent stream pattern at Healdsburg, and apparently throughout the northern Coast Ranges. Average trend is N. 45° W., similar to that of the San Andreas fault.

The strike-slip movements, where they affect the hard brittle rocks older than the Sonoma group, have produced zones of intense fracturing. In many cases the hardest rocks, chert, schist, and igneous types—have persisted as great boulders which have moved and rotated independently in the softer gouge. Erosion leaves them as knobs above the weaker terrain. Likewise, shearing movements have squeezed up and smeared out thin serpentine bodies, often with included blocks of other material.

Strike-slip movements are not easy to demonstrate unless recognizable structure is cut at an angle, or the movement is so recent that some geomorphic expression remains. Fortunately, both criteria can be applied at various points in the Healdsburg quadrangle; otherwise, strike-slip could be mistaken for dip-slip movement in folded beds. Where positive evidence as to direction of movement is lacking, the writer has considered fault zones showing very intense shearing, or development of a secondary shear set, to be strike-slips.

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[37] Jenkins, O. P., Geologic map of California, scale 1 : 500,000, California Div. Mines, 1938.

[38] Lawson, A. C., U. S. Geol. Atlas, San Francisco folio (no. 193), 1914.

The Healdsburg fault best exemplifies the strike-slip type. Along it the Geyserville syncline axis has been sliced and the southwest side moved approximately 3 miles relatively northwest. In addition to the strike-slippage, the perched alluvium at Hill School indicates that the southwest side has moved up about 50 feet rather recently. But despite the uplift of the southwest side, the large horizontal component, in conjunction with south plunge of the Windsor syncline, has resulted in a net stratigraphic downthrow to the southwest, thus mimicking a normal fault.

Upward movement of the southwest side is further indicated by the alluvial area near Chiquita. There the beheaded drainage outlet to the west cannot be definitely located ; it was probably the gap five-eighths of a mile northwest of Chiquita. The subsequent stream which at first flowed north through the pass where the highway is located, was captured and diverted around Hill 188, then captured by the creek flowing south past Chiquita.

Two minor north-trending cross-faults separate from the main Healdsburg fault near Hill School. These are regarded as secondary shears whose angle to the main shear direction has been produced by a rotation of the direction of horizontal compression at the time of movement on the main fault. Thus the main compression, which was north and south, was resolved at the major fault break into a northwest and northeast component. The minor faults are horizontal shears developed along the northeast component.

On topographic maps, the Healdsburg fault zone is traceable southeastward through Bennett Valley, thence along the crest of the central Sonoma Mountains, and into Sonoma Valley at Carriger Creek. It follows the west side of lower Sonoma Valley, probably as far as San Pablo Bay. To the northwest it joins the Alexander fault zone and is traceable past the Boonville road.

A branch fault trending N. 60° W. diverges at Adam and Eve Redwoods and disappears below alluvium. It is directly in line, however, with the Grass Valley fault to the northwest and is undoubtedly a part of it.

The Grass Valley fault shows an oblique movement of which the horizontal component is 1,000 feet; the southwest side has moved northwest. An uncertain, but probably considerable, vertical component is indicated, the south side having risen. This fault is not traceable on topographic evidence more than 2 miles farther northwest. To the southeast it appears to join the Healdsburg fault.

The Wallace Creek fault zone is a complex of slivers bounded by interlacing faults ; width of the network is 0.5 to 1 mile wide. Evidence of the total displacement is lacking. On the northernmost fault near the west edge of the quadrangle, the sandstone-schist contact has been displaced 2,000 feet. A strong vertical component on the southern fault near the Russian River is shown by uplift of Franciscan 400 feet or more above a Sonoma inlier. The isolated Franciscan exposure east of the Russian River probably lies immediately north of the continuation of this fault. The patchy distribution of strata, such as the greenstone at Peaches

Creek indicates considerable horizontal movement; the group of secondary shears to the north is related to the Wallace Creek fault zone.

The southeastward continuation of the Wallace Creek fault zone is lost in Llano de Santa Rosa. However, its projection lines up with the north end of a major fault zone along the west flank of the Sonoma Mountains. This was mapped by Dickerson[39] east of Petaluma; he regarded it as the northern continuation of the Hayward fault. Its passage through the Sonoma Mountains is well marked; it enters just south of Santa Rosa, follows along the base of the oversteepened portion high on the west flank, passes through the Petaluma reservoir and along upper Rodgers Creek, and finally leaves the mountains near the mouth of Tolay Creek, disappearing into San Pablo Bay. A slight bend to the west beneath San Pablo Bay would bring the Wallace Creek fault zone in line with the Hayward fault; but if it continues, instead, with its average bearing, it falls in line with the Pinole fault. The Hayward fault, if projected N. 35° W. to N. 40° W. from the west side of Pinole Point, would line up with the east edge of Petaluma Valley. The correlation of the fault zone in the Sonoma Mountains with the Hayward fault is therefore open to doubt. The Wallace Creek fault zone appears to continue northwestward from the quadrangle boundary at least across the adjoining 7½-minute quadrangle.

The Porter Creek fault zone has fragmented the synclinal area in the lower reaches of Porter Creek. Movement along the component faults is shown as strike-slip on the geologic map, but this was concluded by analogy with other zones in the area rather than from any unequivocal evidence to be found in the zone itself. The amount of displacement along the most northerly fault is not known, for the broken strata could not be correlated. If all movement is considered strike-slippage, right lateral displacement was about 2,600 feet along each of the two central faults, as judged by the position of the Knoxville contact; about 4,200 feet along the south fault, as judged by movement of the Merced contact; and about 3,600 feet along the cross-fault joining the southern pair, as judged by movement of the gabbro.

The three southern faults converge northwestward, and the combined zone is traceable to central Porter Creek. One mile southwest of the quadrangle boundary, a continuation of the zone is indicated by a Merced salient just west of Trenton. Within another mile the Porter Creek fault zone disappears into Llano de Santa Rosa.

The Mount Jackson fault zone is particularly significant, for valuable quicksilver deposits occur along it at the Mount Jackson and Great Eastern mines north of Guerneville. Myers and Everhart[40] mapped the area of the mines, both underground and on the surface, in great detail. Their surface map has been incorporated in the map accompanying this report.

Absence of correlatable strata north and south of the fault zone prevents any calculation of the amount of movement. The width of the zone and the intense crushing, however, place it as a member of the strike-slip system, and an important one. The minor faults which cut the syncline at the head of Porter Creek are secondary shears related to the Mount Jackson fault zone.

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[39] Dickerson, R. E., Tertiary and Quaternary history of the Petaluma, Point Reyes, and Santa Rosa quadrangles, California: California Acad. Sci. Proc., vol. 11, 1922.

[40] Myers, W. B., and Everhart, D. L., op. cit.

The Mount Jackson fault trends southeast from the quadrangle as a wide zone through Forestville, Sebastopol, along the west side of Llano de Santa Rosa, and through the length of the low ridge west of Cotati and Penngrove. South of Penngrove it appears to pass down the northeast side of Petaluma Valley to San Pablo Bay; it may be a northward extension of the Hayward fault. The fault mapped by Johnson [41] 1½ miles southwest of Cotati, along which the Petaluma formation on the west is faulted up against Sonoma and Merced, may be part of the zone. Dickerson [42] shows a fault on the north side of Petaluma Valley, along which Franciscan on the south is faulted against Merced. This may be another segment. These two portions are shown as a single fault on the Geologic Map of California.[43]

To the northwest, the Mount Jackson zone may be followed on aerial photos at least 3 miles beyond the quadrangle. The Meeker Ranch magnesite prospect is located on this fault zone.

In the northeast corner of the quadrangle along upper Little Sulphur Creek, is another of the strike-slip fault system—the Pine Flat fault zone. The amount of movement along this zone cannot be determined, however, for correlatable stratigraphic ties are lacking.

From Pine Flat southeastward the fault zone runs along the west slope of Mount St. Helena. Shortly beyond, it enters upper Napa Valley. Just over a mile northeast of the Healdsburg quadrangle, there are active hot springs on a fault zone that parallels several areas of recent hydrothermal alteration there. The Geysers and Little Geysers are located along it.[44]

Major strike-slip faults of the system maintain a constant trend, averaging N. 40° W. throughout the quadrangle, and apparently for many miles beyond its borders. Related secondary shears run roughly north. The major trend dominates the Coast Ranges from Healdsburg southeast into the Diablo Range, east to the Sacramento Valley, north to the Klamath Mountains, and west to the San Andreas fault. Lawson [45] long ago considered that the coastline between Point Conception and Cape Mendocino must be controlled by faults, one set trending N. 35°-40° W., and another set trending N. 10°-15° W. The strike-slip system, including the related secondary shears, could well account for both these erosional trends along the coast north of Point Arena.

Vickery [46] reported major strike-slip faults in the Livermore region in the northern Diablo Range. In addition to the Hayward fault, he considers the Sunol (Calaveras) and Riggs Canyon faults to be this type. These appear to be the same system as at Healdsburg. The wide Sacramento River passage, however, is an effective barrier to accurate tracing of the faults between the central and northern Coast Ranges. The strike-slip system of the Healdsburg area is regionally of great significance, and mapping in adjoining areas will undoubtedly show its great extension both to the southeast and northwest.

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[41] Johnson, F. A., op cit.

[42] Dickerson, R. E., Tertiary and Quaternary history of the Petaluma, Point Reyes, and Santa Rosa quadrangles, California: California Acad. Sci. Proc., vol. 11, 1922.

[43] Jenkins, O. P., Geologic map of California, scale 1:500,000, California Div. Mines, 1938.

[44] Bailey, E. H., op. cit.

[45] Lawson, A. C., Branner, J. C., Gilbert, G. K., Reid, H. F., and others, The California earthquake of April 18, 1906: Carnegie Inst. Washington Pub. 87, pp. 1-451, 1908.

[46] Vickery, F. P., The structural dynamics of the Livermore region: Jour. Geology, vol. 33, pp. 608-628, 1925.

Displacements along the San Andreas fault in 1906 and the Hayward fault in 1868 are familiar examples of present strike-slip activity. At Healdsburg, geomorphic features such as the perched alluvial valleys, the tilted 200-foot erosion surface east of Maacama Creek, and the as yet incompletely adjusted drainage system all indicate recent movement. Countless cases of stream piracy just completed or in progress are but now bringing the numerous fault-controlled subsequent streams into an integrated system. Latest movement on most faults antedates the 200-foot terrace level.

The earliest strike-slip movement that can be distinguished cut Sonoma and Merced beds. It is probable that the fault zone shown to end west of lower Russian River valley actually cut the young rocks of the Windsor syncline; evidence, however, is concealed by the Russian River alluvium. The Llano de Santa Rosa is flat and without exposures, and is completely devoid of surface indications of the faults. The age of the strike-slip system is therefore placed as Pleistocene-Recent. Initiation of the strike-slip system during the middle Pleistocene orogeny seems a reasonable assumption. If so, the age may be further qualified as middle Pleistocene-Recent.

The strike-slip system with its great northwest shears has formed in response to enormous horizontal compressive forces. Large conjugate shears might also be expected to slice northeast, but these are not found. However, within the body of the rock between major faults, small-scale conjugate shearing has developed with both northeast- and northwest-striking shear planes. Hence, on a small scale, a symmetrical east-west lengthening has occurred; on a large scale, lengthening in only one direction, westward by northwest shear, has been possible. The small vertical components accompanying strike-slip movements have absorbed a part of the compression.

Right lateral movement along all the major strike-slip faults mechanically defines the direction of the causative force as generally north-south. Based on a theoretical study of the relationship between folds and the strike-slip faults in the Livermore district, Vickery [47] concluded that the active stress was rotational and from the south.

At Healdsburg, a vertical component, in addition to the horizontal, is found along many of the faults. The southwest sides have consistently moved up; and, as shown by geomorphic relationships, the rise is not only relative but an actual upthrusting above the previous level. The southwest sides, then, have been imbued with energy greater than that possessed by the northeast sides, an indication that the active force operated northward.

The geomorphic map of California, shows a sharp break between the Coast Ranges structure and the Great Valley. This break is clearly defined topographically from the south end of the valley north to a point beyond Clear Lake. From that point, although the valley edge swings to the east, the dividing line between Coast Ranges structure and the Trinity and Klamath Mountains crystalline area may be projected straight ahead. The Coast Ranges trend and folding are at an angle to this dividing line, not concordant with it. It seems likely, then, that between the Coast Ranges and Klamath Mountain-Great Valley area there is a profound discontinuity at depth; to the east of the line the crust has acted as a rigid block of Klamath Mountain crystallines and Sierra Nevada granite. Against this bulwark, the Coast Ranges have been and are still being shoved by horizontal stress from the south. The rocks cannot shear to the northeast for there is not room for relief in that direction. Therefore they break in the great strike-slip system to the northwest.

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[47] Vickery, F. P., op. cit.

Minor Shearing. The brittle pre-Sonoma formations are intensely sheared down to very fine dimensions, and innumerable small movements have occurred throughout the body of the rock. This shearing is a small-scale expression of the great fault movement along the major strike-slip faults. The intensity and pervasive quality of the shearing results from the brittleness of the rock and the absence of overburden. Along the shear planes, quartz has been deposited as an intricate network of tiny veins.

Oversteepened Dips. The compression which resulted in strike-slippage is responsible also for local vertical to overturned dips near major faults. The largest oversteepened area lies within the Russian River loop between Fitch Mountain and the Alexander fault zone. There, dips are consistently vertical to overturned. This tightening of previously folded rock might be expected to bulge up the surface. Such movement may be the cause of the broad arch in the Sonoma rock between Alexander Valley and Chiquita. On both flanks, the basal Sonoma flows are steepened to between 65° and vertical; over the arch the dips are gentle. The appearance is suggestive of upsqueezing in the older rock, accompanied, perhaps, by actual faulting at the boundaries, the Sonoma being raised passively. This crudely anticlinal area continues southeastward between the Healdsburg and Alexander fault zones, nearly to Hill School.

The oversteepening east of upper Dutcher Creek, along northwest Dry Creek, and at points along the Maacama fault zone is also attributed to the compression which effected strike-slip movement.

Renewed Movements on Old Faults. Later movements have occurred along both the normal and dip-slip faults. The intense shearing in the Black Mountain and Little Sulphur normal fault zones probably indicates strike-slip movement. Recent adjustments along the Maacama and Chianti dip-slip zones have produced small upthrows on the southwest sides. The perched alluvium between Saysal and Gird Creeks and at the head of Miller Creek is evidence of this movement along the Maacama zone; two similar areas east of Chianti attest to such movement along the Chianti zone. In both cases at Chianti, the vertical movement is about 100 feet. These adjustments have been directly opposite in sense to the major dip-slip movements. Whether the readjustments have been accompanied by strike-slip movements is not clearly shown. In the perched alluvium at Miller Creek, the stream is deflected northward around a knob of poorly indurated Sonoma sediment. This suggests that the knob has been moved horizontally. The geomorphic expression of recent movement in the Maacama and Chianti zones is strikingly similar to that shown along the Healdsburg fault at Hill School and Chiquita. The latter localities show good evidence of a large horizontal movement (about half a mile at Hill School) combined with the minor vertical component. Therefore, although the data supporting strike-slip movement are inconclusive for the Maacama and Chianti dip-slip zones, there is a strong suggestion of such.

A great number of recent small movements have fragmented the Sonoma rocks along the Alexander normal fault zone. In most cases, the southwest side has dropped 50 feet or less. The fault in Brooks Creek valley shows an opposite displacement.

GEOMORPHIC EVOLUTION

Many of the more recent geologic events in the northern Coast Ranges may be deduced by geomorphic analysis, for a reference plane has been preserved on the mountain summits. Lawson [48] first recognized that the uniformly accordant ridge crests of the Mendocino Range represent an old erosion surface carved before the mountains had been elevated to their present height. Diller [49] studied the same broad erosion surface in the Coast Ranges and Klamath Mountains farther north.

Mendocino Plateau. Between Healdsburg and the coast, the dissected surface of the Mendocino Plateau is between 1,900 and 2,200 feet in maximum height. These elevations probably represent the approximate elevation of the old erosion surface. They may, however, be considerably below it, for no undissected interfluve flat remains. The erosion cycle is in late youth, with a maximum expression of topographic irregularity; and this condition may be prolonged where uplift keeps pace with erosion. As a result, the divides may have been lowered uniformly, remaining themselves accordant, but no longer showing the actual position of the original surface.

At Healdsburg and in the Sebastopol quadrangle adjoining to the south, there is a notable warping of the plateau surface. A few miles north of Russian River it stands at an elevation of 1,940 feet; in a distance of 14 miles it plunges southward, under Merced strata, until at Estero Americano it is below sea level. Between Estero Americano and Estero San Antonio, the wide divide in gentle hills of Merced strata is 400 to 500 feet in elevation. South of Estero San Antonio, elevations in Merced increase slightly as far as Walker Creek; beyond Walker Creek, the erosion surface rises rapidly from below the Merced to an elevation of 1,000 to 1,300 feet, within 2 miles. Thus, a large-scale down-buckle at least 15 miles wide has affected the erosion surface. The structure produced is a broad syncline in Merced strata; its axis trends eastward and is in the low between Estero Americano and Estero San Antonio. Within the broad downwarp, Merced beds have been preserved; on either side they have been stripped off, and the old surface upon which they were deposited has been bared and modified.

In Healdsburg quadrangle, the surface slopes rapidly southeastward, dropping far below sea level beneath the Windsor syncline. Farther north, the surface slopes more gradually eastward, first to between 700 and 800 feet in the hills between Dry Creek and Alexander Valley, then to 600 feet east of Chianti. East of the Chianti fault zone, the Mayacmas Mountains rise steeply to 3,115 feet at Black Mountain. The Chianti and Maacama fault zones divide the Mendocino Plateau from the Mayacmas Range.

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[48] Lawson, A. C., The geomorphology of the coast of northern California: Univ. California, Dept. Geol. Sci. Bull., vol. 1, no. 8, pp. 241-272, 1894.

[49] Diller, J. S., Topographic development of the Klamath Mountains: U. S. Geol. Survey Bull. 196, pp. 1-69, 1902.

Mayacmas Mountains. The erosion surface is similarly registered in the Mayacmas Mountains by a general accordance of summits. Diller noted this feature between the Russian River and Clear Lake. East of Healdsburg a northeastward surface tilt is shown by a drop in elevation from 4,000 feet (the Sonoma-Franciscan contact at Cobb Mountain) to about 2,000 feet at Clear Lake. Along the crest of the range on either side of Cobb Mountain, the elevation is above 3,000 feet. While this is considerably below the height at Cobb Mountain, it is distinctly higher than the elevations to the northeast. That it is lower than Cobb Mountain is attributed to the fact that protective Sonoma lavas have been stripped off and the original surface eroded.

Age of the Erosion Surface. There is some doubt as to the time at which the erosion surface was developed. The generally planar aspect of the surface upon which Merced and Sonoma rocks were unconformably deposited is evidence that a well-developed erosion surface existed in the Healdsburg area by late Pliocene. As shown by the irregular distribution and local overthickening of basal Sonoma lavas, the surface was not devoid of topography, for these variations were probably controlled by gentle hills and valleys. Nevertheless, the erosion surface may be used to indicate in a general way the diastrophism which has occurred since deposition of Merced and Sonoma strata.

Uplift of the Erosion Surface. A great differential in amount of uplift between the Mendocino Plateau and Mayacmas Mountains is evident in the Healdsburg area. The erosion surface, which lies below sea level beneath the Windsor syncline, stands at 4,000 feet along the crest of the Mayacmas Range. The Merced formation of the Healdsburg area, deposited under shallow marine conditions, now has an elevation not much above sea level; that part of the Mendocino Plateau block on which it lies, therefore, has been relatively stable. With this as a plane of reference it is clear that the Mayacmas Range has reached its present elevation by active rise of that block. The sharp break between the Mendocino Plateau and Mayacmas Mountains falls at the Maacama fault zone, a major dip-slip system showing relative movement in the same sense in which the large blocks have moved. It is probable, therefore, that the active uplift of the Mayacmas Mountains was effected along the Maacama and Chianti zones.

Uplift of the Mayacmas Mountains was not uniform; rather, tilting was to the northeast. Similar tilting of the Mendocino Plateau carried Sonoma rock well below sea level in the Windsor syncline.

The differential movement at Healdsburg is a local phenomenon concurrent with a general uplift of both the Mendocino Plateau and Mayacmas Mountains to the north. For some reason, the Mendocino Plateau block at Healdsburg rose to the north and sank to the south and southeast, although uplift of the Coast Ranges appears to have been uniform to the north. The area of division between the two blocks is along the line marked by extrusion of Sonoma volcanics; a line of weakness seems to have long predated the dip-slip faulting. What density relationships were effected deep in the crust by the withdrawals and intrusion of magma during Sonoma time is unknown. Variations in these may have been responsible for the different responses of the two blocks to later uplift.

It seems reasonable to place initiation of uplift in the middle Pleistocene, the time of a major disturbance in the central and southern Coast Ranges. Since a graduated system of marine and rivercut terraces leads down to the present level, and the lower levels are young and well preserved, it is apparent that terrace levels now forming may shortly be raised to stand as one more mark of the progress of uplift. The end of this event has not been reached.

Russian River. Holway's[50] conclusions regarding the history of the Russian River, made at a time when only the crudest maps were available in this area, are largely substantiated by the present work. Only a few specific details may be added to his excellent analysis.

In brief, he concluded that the lower Russian River, which traverses the Mendocino Range through a deep canyon cut in resistant Franciscan rock, is antecedent, that its course had been consequent across the Mendocino block before uplift. The longitudinal segment, stretching northward from Llano de Santa Rosa, he considered subsequent. He cited the narrow canyon cut through Sonoma rock 1 mile south of Jimtown in Alexander Valley as evidence of local superposition, for the wide-open valley to the east has been by-passed.

Holway has shown that consequent drainage, roughly paralleling the Russian River, once flowed across the Mendocino block to the north. Best example is the Navarro River, which drains northwest into the Pacific from the crest of the Mendocino Range some 20 miles northwest of Healdsburg. The Navarro lies in direct line with a long valley trending southeast from the crest to join the Russian River. This segment, in turn, is directly in line with Big Sulphur Creek which flows into the Russian River from the southeast. At Yorkville, Holway found a windgap between the Navarro and the Russian River tributary, indicating that the Navarro was beheaded by extension of the Russian River as a subsequent stream. He attributed the rapid growth of the subsequent portion of the Russian River to the presence of a line of weakness, probably a fault, and noted the probable presence of a fault delimiting the end of the long gorge northeast of Cloverdale.

The present work at Healdsburg shows the character of the line of weakness. It is determined by the strike-slip fault system. The entire course of the river from Ukiah (40 miles northwest of Healdsburg) to Alexander Valley is composed of straight segments trending S. 40° E., joined together by south-trending segments. The S. 40° E. portions are following the fault zones which at Healdsburg lie along Alexander Valley and in the Mayacmas Mountains. Holway's fault northeast of Cloverdale is the extension of the Chianti zone.

Along the subsequent portion of the Russian River, stretches of abnormally wide valley are interspersed with segments of narrow canyon. Alexander Valley and the valley below Healdsburg are two such overwidened portions; at Cloverdale and Hopland are others. In the Healdsburg quadrangle it is clear that the abnormal width depends on the structurally controlled presence of weak rocks. The river has been able to erode wide valleys in these, but has cut only narrow valleys through the harder rock. The weak rocks beneath Alexander Valley are Knoxville shale and poorly consolidated Sonoma sediment; beneath the lower valley, they are Sonoma sediment. Sufficient time has elapsed in downcutting the resistant rock between overwidened valleys to permit the formation of wide erosion surfaces where weaker material is present. No doubt, the development of the overwidened valleys north of Healdsburg has been similarly controlled.

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[50] Holway, R. S., The Russian River: a characteristic stream of the California Coast Ranges: Univ. California Pub. Geography, vol. 1, no. 1, pp. 1-60, 1913.

The anomalous passage through Sonoma rock south of Jimtown appears to be explainable only by superposition. Flat-lying gravels 240 feet above present drainage level at Hopland may have formed the surface from which the river became superimposed. Field evidence supports this. A level 200 feet above drainage is preserved at Manzanita School, southwest of Wilson Grove, north of Fitch Mountain, and at Maacama Creek. This is also the elevation of the hill at Jimtown. At Manzanita School the terrace is fill; therefore, a subsidence must have taken place at least once during the general uplift of the northern Coast Ranges. As a result of the subsidence the pre-existing valleys were filled with gravel. Subsequent resumption of uplift permitted renewed erosion to clear away the gravels rapidly; only remnants, like the terrace at Manzanita School, can now be seen. The wide development of cut terrace levels at this stage indicates a lengthy stillstand. Depth of the fill at Manzanita School is 150 feet, if the outcrop of Franciscan in the right-angled bend of the road 1 mile northwest of Manzanita School represents the old valley floor. This is a measure of the amount of subsidence.

The curious sinuate course of the river through the canyon between Alexander Valley and Healdsburg was considered by Holway to have arisen by meander intrenchment. Present mapping shows, rather, that this portion is structurally controlled. Nearly the entire course lies within readily erodable Knoxville shale. The river has occupied this canyon at least since the subsidence which produced the 200-foot erosion level.

A striking break in the divide between Alexander Valley and Healdsburg is present at Lytton. It has the aspect of a windgap. Why the Fitch Mountain Canyon was occupied in preference to this broad low in soft sediments is difficult to explain. A subsidence earlier than that identified with the 200-foot erosion and fill level, coupled with development of subsequent streams at Fitch Mountain, could account for it. If preceding the supposed subsidence, subsequent streams at Fitch Mountain had work headward both from east and west in the readily erodable Knoxville shale belt, a relatively low divide could have been carved. Regional subsidence would produce potent aggregation in the Russian River channel at Lytton, weak aggregation in the subsequent stream channels at Fitch Mountain, but none in the divide there. Aggradation at Lytton, if long continued, could have raised the elevation higher than the divide at Fitch Mountain. Likewise aggregation in all streams entering Russian River east of the Lytton Gap would raise the entire Alexander Valley areas and the Russian River would divert from the channel at Lytton to cross the lower divide at Fitch Mountain. With cessation of subsidence and renewed downcutting, the new course would become entrenched and secured. Evidence to confirm this is lacking.

Holway showed that the Russian River never has flowed down Llano de Santa Rosa to San Pablo Bay, although the highest divide between the present course and the bay is the low ridge along the west edge of the Windsor syncline. The river was evidently seated very early at the Sonoma-Franciscan contact. Ever since, a low cuesta of Sonoma strata has stood between it and the wide valley open to the south to San Pablo Bay. It must have been a very tenuous dividing line at the time of subsidence, for the 200-foot erosion level is nearly as high as the cuesta.

The course of the Russian River through the Mendocino Range is antecedent. The meanders between Wilson Grove and Guerneville are probably structurally controlled. Each of the northwest-flowing segments is along a member of the strike-slip fault system.

The erosion level last developed, which carries across the wide valleys and far up the tributaries, is correlated with a very late subsidence which drowned many valleys along the coast south of the Russian River and created San Francisco Bay. Most recently, a slight uplift has caused the Russian River to begin active erosion once more; the river has already cut 20 to 25 feet into the surface.

Holway ascribed the impeded drainage in Laguna de Santa Rosa, a few miles south of the Healdsburg quadrangle, to very recent folding in the Windsor syncline. However, the sloughs lie along projections of the Porter Creek and Mount Jackson strike-slip fault zones. They are possibly sags caused by recent fault movement.

MINERAL RESOURCES

Deposits of rocks and minerals in the Healdsburg quadrangle have been discussed in a report on Sonoma County by Honke and Ver Planck.[51] Of these, only quicksilver, crushed rock, and sand and gravel, are in sufficient quantity to be economically important.

Building Stone. A small quarry about 2 miles southwest of Healdsburg, near Felta school, supplied building stone for local use in the early 1900's. The rock is Sonoma basalt with well-developed columnar jointing. From the columns, flat stone can be broken. Quarry output was probably used entirely for winery construction in the neighborhood.

Chromite. Chromite is commonly present as a minor accessory in the serpentinized peridotites of the Healdsburg quadrangle. In the serpentine along the ridge northeast of Healdsburg, localized chromite concentrations in pods yielded a few sacks of ore during World War I. The small scale operation exhausted what chromite was exposed on the surface and no development work was undertaken.

Crushed Rock. Rock suitable for road metal and construction fill is found abundantly in the Healdsburg quadrangle. Franciscan greenstone and chert, where thoroughly sheared, break down readily to make an admirable unpaved road surface, and are much used for ranch and county fire roads within the area. Firmly cemented massive Franciscan sandstone is usable for construction fill and is quarried by Siri and King Construction Company in sec. 20, T. 8 N., R. 10 W.

Copper. Prospects for copper have failed to find commercial quantities in the Healdsburg quadrangle. The pits north of Chapman Brook, in sec. 4, T. 9 N., R. 10 W., all prospect faulted gabbro. Small quantities of malachite, azurite, and cuprite are present in shattered quartz veins.

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[51] Honke, Martin T., Jr., and Ver Planck, William E., Jr., Mines and mineral resources of Sonoma County, California: California Jour. Mines and Geology, vol. 46, pp. 83-141, 1950.

To the northwest, in sec. 32, T. 10 N., R. 10 W., adits penetrate metamorphosed greenstone. No ore was seen on the dumps.

One other prospect for copper is located on the south slope of Wild Hog Hill, where small flecks of native copper are present in sheared schist contained within a large serpentine body.

The prospecting for copper was carried out 70 to 80 years ago.

Hematite. Brilliant red hematite incrustations on weathered chert were formerly mined in sec. 18, T. 8 N., R. 9 W., for local use as pigment in barn paint. The mine has been long abandoned.

Lime Rock. An old marble quarry and kiln are located in sec. 14, T. 10 N., R. 9 W. The marble is gray and finely crystalline, but in scattered patches some calcite crystals reach a length of as much as 2 inches. The material is metamorphosed Franciscan limestone. Lime was first burned here about 1880. The body is far too small to be of economic importance today.

Manganese. Manganese oxide is common as stains on Franciscan chert at numerous localities within the Healdsburg quadrangle, but does not occur in commercial quantity. A few tons of ore were produced during World War I from the pit in sec. 8, T. 10 N., R. 8 W., where the oxide is present in typical association with Franciscan chert and greenstone. Details on manganese deposits of the entire area have already been published.[52] Of 18 additional manganese deposits reported by Trask in Sonoma County, 5 are in the Healdsburg quadrangle.[53] The only recorded production was 10 tons of 50 percent manganese in 1934, from the Dreamland mine northwest of Mark West Springs.[54]

Petroleum. No oil or gas has been found in the Healdsburg area. The Mortara Oil Company drilled three dry holes in Alexander Valley, data for which are included below.

T.	R.	Sec.		Year	Depth in ft.	Bottomed in
10N	9W	(22)	Mortara Oil Co.	ca. 1935	200	Franciscan
* 9N	8W	8	Mortara Oil Co. "Bidwell" No. 1	1936	2881	Franciscan
* 9N	8W	8	Mortara Oil Co. No. 2	1937	3772	Franciscan (?)

* Data from California Division Mines Bull. 118, p. 661.

Quicksilver. The Mount Jackson mine, sec. 16, T. 8 N., R. 10 W., was operating in 1950. Ore is cinnabar in silica-carbonate rock gangue localized along the Mount Jackson fault zone. Combined total production of the Mount Jackson and Great Eastern mines, which have been worked together throughout most of the productive period, has been 58,467 flasks, 1875-1945. This is more than two-thirds of the total quicksilver production of Sonama County. Myers and Everhart[55] published a detailed surface and subsurface study of this mining district, and the reader is referred to that for further information.

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[52] Jenkins, O. P., et al., Manganese in California: California Div. Mines Bull. 125, 1943.

Trask, Parker D., et al., Geologic description of the manganese deposits of California: California Div. Mines Bull. 152, 1950.

[53] Trask, Parker D., et al., op. cit., pp. 283-286.

[54] Trask, Parker D., et al., op. cit., pp. 283-284.

[55] Myers, W. B., and Everhart, D. L., Quicksilver deposits of the Guerneville district, Sonoma County, California: California Jour. Mines and Geology, vol. 44, pp. 253-277, 1948.

An abandoned mine in sec. 31, T. 10 N., R. 8 W., has seen attempted production during both world wars. The ore is cinnabar in silica-carbonate rock and shattered Franciscan sandstone along the Maacama fault.

Numerous prospect pits and adits, scattered widely in the Healdsburg quadrangle, have been opened to test silica-carbonate ledges.

Sand and Gravel. Six companies at present take sand and gravel in quantity from the Russian River and Dry Creek channels to be used for construction purposes. These are Basalt Rock Company, Dry Creek Gravel Company, Harvey Taylor, Hein Brothers, Maxwell Brothers, and Onsrud Construction Company. The Basalt Rock Company is by far the largest producer and operates an extensive modern plant just southeast of Healdsburg.

Tin. Fault gouge assaying 1.55 percent stannous oxide is reported from the prospect in sec. 13, T. 9 N., R. 10 W. The gouge zones occur along small faults cutting Franciscan chert. Commercial quantities have not been found.

GEOLOGIC HISTORY

Many events, particularly in early Tertiary, cannot be accurately dated at Healdsburg, for no record has been preserved.

During Upper Jurassic time Franciscan shallow marine clastics were deposited in a geosyncline developed at the foot of highlands to the west. The western land, which served as a source for the enormous volume of sediment, must have risen in pace with erosion, for no marked reduction in grain size occurs throughout the Franciscan sediments. In the upper part of the Franciscan are large volumes of basalt, dacite, and agglomerate erupted from submarine volcanos; basic and ultrabasic magma was intruded as sills, plugs, and dikes. The submarine eruptions were accompanied by chemical deposition of radiolarian chert from the siliceous marine waters. Pneumatolytic metamorphism, produced by high temperature and abundant volatiles in the intrusives, locally affected both sediments and volcanic rocks.

With continued subsidence and a waning of igneous activity, the latest Jurassic Knoxville marine shale was deposited. Upper Jurassic rocks were warped sometime before the Upper Cretaceous; however, the time of the warping and the trends imposed are unknown.

A re-elevation of the old land to the west, possibly with Franciscan lapping upon it, contributed great quantities of conglomerate to a rapidly sinking basin in Upper Cretaceous. The conglomerate of the Geyserville syncline represents a piedmont or marginal phase.

In the upper Eocene-Oligocene interval, the rocks were moderately compressed to form a series of open folds trending N. 70° W. Slight subsidence occurred and the fresh and brackish water conglomerate and siltstone, now exposed along Little Sulphur Creek, accumulated. Subsequently, the folded rocks and newly deposited conglomerate and siltstone were cut obliquely by normal faults, and grabens were produced.

Whether Miocene strata were deposited over the folded rock is unknown, but if so, they were completely stripped off by late Pliocene and a gently undulating erosion surface truncating the older rocks was cut.

Crustal disturbance in late Pliocene resulted in volcanic activity along the line of the present Sonoma Mountains and subsidence below sea level of the land to the west. The volcanos erupted the tuffs and basalts of the Sonoma group while concurrent stream action deposited thick conglomerates and sandstones as an apron between the volcanic cones and the strand. The finer clastic material which reached the shallow sea, accumulated as the fossiliferous Merced sandstone.

Soon after the Sonoma-Merced strata were deposited, probably in the lower Pleistocene, gentle compression formed minor flexures, now preserved in the Brooks Creek area. A time interval elapsed, probably a short one, during which an erosion surface was developed on the Sonoma-Merced rocks.

In middle Pleistocene, uplift began which has continued intermittently to the present. First, consequent drainage was established across the Mendocino Plateau block, a forerunner of the system of today. The uplift has never been too swift for the early drainage to keep pace; the present westerly flowing rivers are antecedent.

The uplift appears to have been uniform to the north, but in the Healdsburg quadrangle, the southern end of the Mendocino Plateau lagged behind or was negatively affected. Independently, the Mayacmas Mountains rose and tilted northeastward, the differential motion being taken up by formation of major dip-slip faults, the Maacama and Chianti zones. An east tilt was also imparted to the south end of the Mendocino Plateau which carried Sonoma rock to below sea level.

At some time during the uplift, or perhaps accompanying it throughout, horizontal pressures directed from the south produced an intricate system of strike-slip faults. Along these major shears the southwestern sides have moved many thousands of feet northwest and, in later stages, upward to a small degree. These movements are still in progress.

Wave-cut terraces along the Pacific Coast have registered the course of uplift over 1520 feet of elevation. During the latest stages, river terraces from 400 feet above drainage, downward, have preserved a record of the movements.

In the Healdsburg quadrangle, filled terraces 200 feet above river level, attest to an interval of subsidence superimposed on the general uplift. At this time, the land was depressed about 150 feet as indicated by thickness of gravels deposited. Since then, lower terraces register periods of stillstand during later uplift. The broad fill now covering the wide valleys shows a second period of subsidence, correlated with drowning of valleys southward along the coast and the formation of San Francisco Bay. The most recent event is a slight uplift which has rejuvenated the Russian River, so that it is now cutting deeply into the last broad valley fill.

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MINERALOGY OF THE CALIFORNIA GLAUCOPHANE SCHISTS*

By George Switzer **

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ABSTRACT

Glaucophane schists are of widespread occurrence in the Upper Jurassic Franciscan group in the Coast Ranges of California. The schists described herein are principally from areas north of San Francisco Bay: Tiburon (Marin County); Camp Meeker, Porter Creek, and Mill Creek (all in Sonoma County); and Syke Ranch near Laytonville (Mendocino County).

The term glaucophane schist is used to include a wide variety of glaucophane-bearing rocks, and those closely related containing little or no glaucophane, with textures varying from schistose to granulose. Four major types are glaucophane-

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clinozoisite-muscovite-garnet schist, glaucophane-muscovite-garnet schist, glaucophane-muscovite-diopside-jadeite schist,[1] and diopside-jadeite-garnet granulite. Numerous minor types include glaucophane-garnet-albite granulite, glaucophane-muscovite schist, glaucophane-lawsonite schist, glaucophane-biotite-quartz schist, hornblende granulite, hornblende-garnet granulite, and lawsonite-chlorite schist.

Optical data and chemical analyses are given for albite, glaucophane-crossite-riebeckite series, tremolite-actinolite series, zoisite-clinozoisite-epidote group, lawsonite, muscovite, pumpellyite, and diopside-jadeite. Differential thermal curves are shown for lawsonite and pumpellyite, and the tabular, prismatic, and equidimensional crystal habits of lawsonite are discussed and illustrated. The thermal analysis of pumpellyite shows that water in the formula is present in part as (OH) and in part as H_2O. The occurrences of antigorite, apatite, chlorite, garnet, hornblende, quartz, rutile, sphene, sulfides of iron and copper, and talc are described.

The 30 different minerals found in the glaucophane schists were successfully introduced over a considerable time interval and the schists have been strongly affected by hydrothermal activity. A more or less typical sequence of mineralization is that in the Camp Meeker area: diopside-jadeite, garnet, hornblende, muscovite, clinozoisite, zoisite, apatite, actinolite, glaucophane, pumpellyite, sphene, chlorite, and pyrite. Pumpellyite, lawsonite, sphene, chlorite, pyrite, and albite are often in veins or seams.

INTRODUCTION

The glaucophane schists found in the Coast Ranges of California present several problems to the geologist which have caused considerable interest and controversy. The question of chief interest concerns the mode of origin of these unusual glaucophane-bearing rocks. Questions of purely mineralogical interest arise concerning several unusual minerals of the schists while an inseparable companion problem involves the serpentinized peridotite intrusives which are closely associated with the glaucophane schists. It is the purpose of the present paper to describe in detail the mineralogy of the schists examined in various areas in Marin, Sonoma, and Mendocino Counties during the summers of 1939 and 1940.

Acknowledgments

Field work for this study of the California glaucophane schists was made possible by financial aid received from the Holden Fund of the Department of Mineralogy, Harvard University, and from Mr. M. Vonsen of Petaluma, California. Professors Charles Palache and Esper S. Larsen of Harvard University gave generously of their time in aid of many sorts. The differential thermal curves of lawsonite and pumpellyite were very kindly prepared by George T. Faust of the U.S. Geological Survey.

GLAUCOPHANE SCHISTS AND RELATED ROCKS

The term glaucophane schist is used in a general sense to include all rock types making up this particular group, of which glaucophane-bearing rocks are members. Thus it includes not only rocks containing glaucophane, but closely related rocks containing little or no glaucophane. Texturally the rocks may vary from schistose to granulose.

The textural and mineralogical variability of the California glaucophane schists is so great that it is difficult to give the schists a systematic petrographic description. Most outcrops show a well-defined schistose structure, but schistosity may be weak or absent. Strong foliation, due to the aggregation of some particular constituent into lenses, streaks, or irregular bands, is a common feature. The less common minerals of the schists are found as local segregations.

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[1] *Diopside-jadeite* in this paper refers to the solid solution, as a mineral.

The glaucophane-bearing and related rocks in the areas studied have been divided into four major types, plus a larger number of minor types. The major types are glaucophane-clinozoisite-muscovite-garnet schist, glaucophane-muscovite-garnet schist, glaucophane-muscovite-diopside-jadeite schist and diopside-jadeite-garnet granulite. Of the numerous minor types the following are examples: glaucophane-garnet-albite granulite, glaucophane-muscovite schist, glaucophane-lawsonite schist, glaucophane-biotite-quartz schist, hornblende granulite, hornblende-garnet granulite, and lawsonite-chlorite schist.

DESCRIPTIVE MINERALOGY

About 30 distinct mineral species were found as constituents of the glaucophane schists in the areas studied. These are listed alphabetically in table 1. A few minerals of secondary origin, in particular calcite, limonite, and malachite, have not been included.

The localities mentioned in the following pages are shown on the index map, figure 1.

Table 1. Minerals of the California glaucophane schists.

- Albite
- Amphibole group
    - Glaucophane-riebeckite series
    - Tremolite-actinolite series
    - Hornblende
- Antigorite
- Apatite
- Chlorite
- Epidote group
    - Zoisite
    - Clinozoisite-epidote series
- Garnet
- Lawsonite
- Mica group
    - Muscovite
    - Fuchsite
    - Biotite
- Pumpellyite
- Pyroxene (diopside-jadeite)
- Quartz
- Rutile
- Sphene
- Sulfides
- Talc

Albite

Albite in the glaucophane schists and associated rocks is a common mineral and is found in three distinct occurrences, but always of the same composition.

Albite is found most commonly as narrow veins in glaucophane schist, in part massive but also developed as sharp crystals projecting into interior open spaces. The crystals are twinned, made up of two individuals, and are tabular parallel to $\{010\}$. They range in size from 1 millimeter to 20 millimeters.

A second occurrence of albite is as the granular groundmass of glaucophane-garnet-albite granulite. The albite grains of the granulite are commonly untwinned, and are fairly uniform in size, about 0.5 millimeter in diameter.

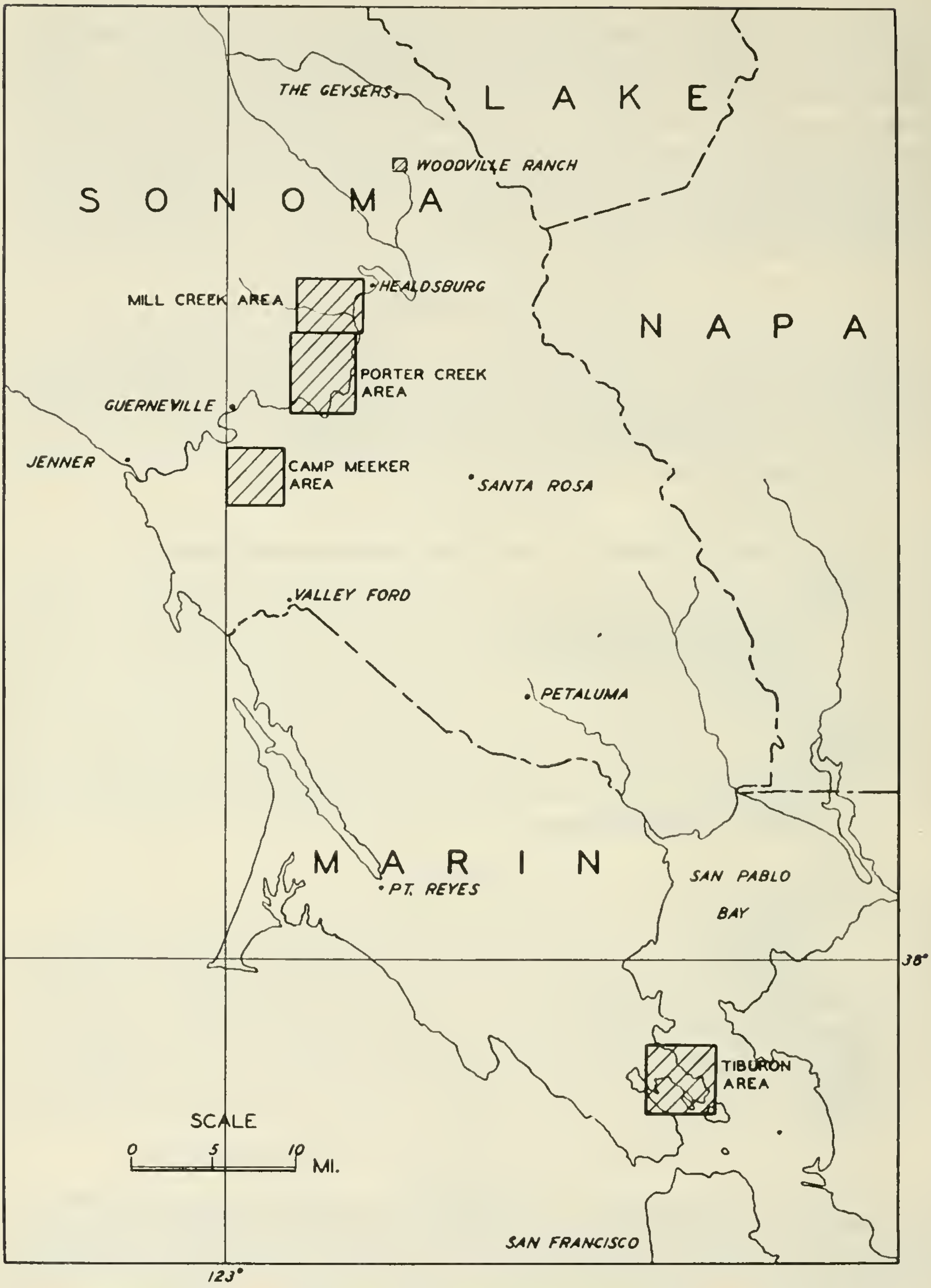

Figure 1. Index map of some glaucophane schist localities in northern California

The third occurrence of albite is in veins up to 5 centimeters in width cutting greenstones, which are closely associated with glaucophane schist. In these veins the albite is in coarsely crystalline, massive form.

Determination of the refractive index of material of each type of occurrence gave $\beta = 1.529\text{-}1.531$ ($\pm$ 0.002). The composition of the albite according to these data is approximately $Ab_{98}An_2$.

One analysis has been made [2] of albite of the first type. The material is described as coarsely crystalline albite from a vein 6 inches wide, cutting glaucophane schist. The analysis is as follows: SiO_2, 67.09; Al_2O_3, 20.47; CaO, 0.24; Na_2O, 10.96; H_2O (—), 0.57; H_2O (+), 0.59; sum 99.62. The analysis calculates to $Ab_{97.6}An_{2.4}$.

Glaucophane-Riebeckite Series

Distinct species of the glaucophane-riebeckite series include glaucophane, crossite, and riebeckite. Glaucophane is the characteristic mineral of the California glaucophane schists, and although some members of the schist group contain no glaucophane, in general it is one of the major constituents of these rocks. The other members of the series are rare in the California rocks. Crossite was found in small amounts in six widely scattered localities, and riebeckite at only one locality.

Members of the glaucophane-riebeckite series found in the areas studied by the writer cover a rather wide range in composition, as shown by the data summarized in table 2. Optical constants are given for seven specimens chosen from various localities to represent the maximum composition range found. Numbers 1 to 3 are glaucophane, numbers 4, 5, and 6 are classed as crossite because of the transverse position of the optic plane, and number 7 is riebeckite.

Four chemical analyses had been made of California glaucophane up to the time the present work was undertaken. Unfortunately, most of these are old, and only one is accompanied by optical data. In order to improve these data two new analyses have been made. These are given in table 3, columns 5 and 6, along with the four older analyses.

Zoned soda-amphiboles are common in various rocks of the glaucophane schist group. Three types of zoned crystals were observed: (1) glaucophane-actinolite, (2) glaucophane-hornblende, and (3) crossite-glaucophane. Glaucophane-actinolite zoning is characterized by the constant appearance of the glaucophane on the periphery of the crystals. In some specimens glaucophane is present only as a very narrow rim, gradually fading into the green interior of actinolite. In others the crystals may be almost wholly glaucophane, with occasional small relict cores of actinolite remaining. In most cases the zoning is not sharp.

Glaucophane-hornblende zoning is uncommon. In a few rocks composed almost entirely of bluish-green hornblende, a narrow, irregular peripheral zone of glaucophane about hornblende is occasionally observed.

Specimens from various localities show blue glaucophane crystals surrounded by a peripheral zone of deeper blue crossite.

Members of the glaucophane-riebeckite series in the California rocks studied show a considerable range in habit. The crystals are always prismatic and some are fine acicular crystals in matted aggregates. Maximum size attained by single crystals is approximately 2 by 20 millimeters.

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[2] Blasdale, W. C., Contributions to the mineralogy of California: Univ. California, Dept. Geol. Sci. Bull., vol. 2, no. 11, pp. 327-348, 1901.

Table 2. Optical data of California glaucophane-riebeckite.

	1	2	3	4	5	6	7
α β γ	1.623 1.637 1.641	1.622 1.641 1.644	1.637 1.646 1.652	1.648 1.654 1.655	1.651 1.656 1.659	1.659 1.663 1.666	1.680 1.683 1.685
Sign 2V	(—) 40°	(—) 35°	(—) 30°	(—) 10°	(—) 30°	(—) 50°	(—) 50°
Dispersion	$r < v$ moder.	$r < v$ moder.	$r < v$ strong	$r > v$ strong	$r > v$ strong	$r > v$ strong	strong
Orientation	$Y = b$ $Z{:}c = 7°$	$Y = b$ $Z{:}c = 9°$	$Y = b$ $Z{:}c = 8°$	$Z = b$ $Y{:}c = 2°$	$Z = b$ $Y{:}c = 2°$	$Z = b$ $Y{:}c = 2°$	$Z = b$ $Y{:}c = 5°$
X	pale yellow	pale yellow	pale yellow	pale yellow	pale yellow	pale yellow	dark blue
Y	violet blue	violet blue	violet blue	blue	blue	deep blue	brown
Z	deep blue	deep blue	deep blue	violet	violet	deep violet	dark blue
Specific gravity				3.23 ± (0.01)		3.22 ± (0.01)	3.40 ± (0.03)

Indices of refraction, nos. 1-6, ±0.002; no. 7, ±0.005.

1. Glaucophane—Porter Creek, Sonoma County.
2. Glaucophane—Camp Meeker, Sonoma County.
3. Glaucophane—Porter Creek, Sonoma County.
4. Crossite—Mill Creek, Sonoma County.
5. Crossite—Mill Creek, Sonoma County.
6. Crossite—Berkeley. (Type material, Harvard Collection No. 12873.)
7. Riebeckite—Mill Creek, Sonoma County.

Table 3. Chemical analyses of California glaucophane.

	1	2	3	4	5	6
SiO_2	54.52	52.39	54.72	55.02	54.40	49.95
TiO_2	0.39	0.14			0.31	0.11
Al_2O_3	9.25	11.29	8.27	4.75	5.62	4.23
Fe_2O_3	4.44	3.74	7.03	10.91	11.04	16.93
FeO	9.81	9.13	11.82	9.46	9.97	13.05
MnO	0.46	trace	0.36	trace	0.14	4.95
MgO	10.33	11.37	7.26	9.30	9.06	3.52
CaO	1.98	3.03	1.58	2.38	1.56	0.39
Na_2O	7.56	6.14	6.31	7.62	5.86	4.94
K_2O	0.16	trace	0.40	0.27	0.09	0.32
$H_2O(+)$	1.78	2.57	1.96		2.01	0.87
F					0.03	none
	100.68	99.80	100.14	99.70	100.09	99.26

1. Glaucophane—from glaucophane schist, San Pablo, California. W. C. Blasdale,[1] analyst.
$(Na,Ca,K)_{2.4}(Mg,Fe'')_{3.3}(Al,Fe''')_{2.1}Si_{7.7}O_{22}(OH)_{2.0}$.

2. Glaucophane—from glaucophane schist, San Pablo, California. W. C. Blasdale,[2] analyst.
$(Na,Ca,K)_{2.2}(Mg,Fe'')_{3.5}(Al,Fe''')_{1.9}Si_{7.5}O_{22}(OH)_{2.0}$.

3. Glaucophane—Berkeley, California. W. Kunitz,[3] analyst. Optical data given by Kunitz indicate that this material is glaucophane, although he calls it crossite.
$(Na,Ca,K)_{2.1}(Fe'',Mn,Mg)_{3.0}(Al,Fe''')_{2.1}Si_{7.8}O_{22}(OH)_{1.9}$.

4. Crossite—Berkeley, California. W. S. T. Smith,[4] analyst.
$(Na,Ca,K)_{2.5}(Mg,Fe'')_{3.3}(Al,Fe''')_{2.0}Si_{8.2}O_{23}(OH)_{1.0}$.

5. Crossite—Berkeley, California. F. A. Gonyer, analyst. Analysis made on type material obtained from C. Palache, optical data by Switzer given in table 2, column 6.
$(Na,Ca)_{1.9}(Fe'',Mn,Mg)_{3.1}(Fe''',Al)_{2.0}(Si,Al,Ti)_{8.0}O_{22}(OH)_{2}$.

6. Riebeckite—Mill Creek, Sonoma County, California. F. A. Gonyer, analyst. Optical data given in table 2, column 7. $(Na,K,Ca)_{1.8}(Fe'',Mn,Mg)_{3.2}(Fe''',Al)_{2.1}(Si,Al)_{8.2}O_{23}(OH)_{0.9}$.

[1] Blasdale, W. C., op. cit.

[2] Blasdale, W. C., op. cit.

[3] Kunitz, W., Die Isomorphieverhaltnisse in der Hornblendegruppe: Neues Jahrb. f. Min., Band 60, Abt. A., pp. 171-250, 1930.

[4] Palache, C., On a rock from the vicinity of Berkeley containing a new soda amphibole: Univ. California, Dept. Geol. Sci., Bull., vol. 1, no. 6, pp. 181-192, 1894.

Tremolite-Actinolite Series

Amphiboles of the tremolite-actinolite series are abundant in the areas studied. Deep green actinolite is a common mineral, and is found as a constituent of large masses of glaucophane schist.

A common occurrence of actinolite is in spherical or ellipsoidal nodules of long radiating crystals, embedded in glaucophane schist. These nodules have smooth rounded surfaces and make sharp contact with the surrounding rock. They may be pure actinolite, or actinolite and talc intergrown. In size they range from 5 centimeters in diameter up to several meters. Individual crystals in some of the larger nodules have been observed having a length of 50 centimeters.

In all occurrences studied the deep green actinolite is very constant in its optical properties. Pale-colored, low-iron members of the tremolite-actinolite series are uncommon in the California glaucophane schists.

Three chemical analyses have been made of tremolite-actinolite from the California glaucophane schists by W. C. Blasdale.[3] These, combined with optical data determined by the writer, show this material to be typical tremolite-actinolite.

Hornblende

Hornblende is an abundant mineral in the glaucophane schists, and some rock types of the schist group are composed largely or entirely of this mineral.

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[3] Blasdale, W. C., op. cit.

No chemical analysis has been made of the hornblende, but all occurrences in the schists have essentially the same composition and are common hornblende. Optical properties from two different localities are given in table 4.

Table 4. Optical constants of hornblende.

1	2
α 1.658	1.657
β 1.670	1.668
γ 1.680	1.680
Op. char. (—)2V = 75°	(—) 2V = 75°
Orient. Y = b	Y = b
Z:c = 20°	Z:c = 16°
X pale yellow	pale yellow
Y olive green	olive green
Z bluish green	bluish green

Indices of refraction ± 0.002.

1. Hornblende—from hornblende-garnet granulite. Occidental WPA quarry. Camp Meeker area.

2. Hornblende—from hornblende granulite. Tiburon Peninsula.

Antigorite

Antigorite was found at only one locality, in the Mill Creek area, as a constituent of a member of the glaucophane schist group. The rock is an antigorate granulite and is composed essentially of a fine-grained mass of platy antigorite crystals. In hand specimen it is pale green, in thin section colorless.

Apatite

Apatite is a minor mineral in the California glaucophane schists. It is found in a few localities in small amount, as veins of white, coarsely crystalline material up to 2 centimeters wide. Occasionally subhedral crystals are found growing in cavities.

The largest crystal seen is from near Valley Ford, in the Camp Meeker area. It is a rough, tabular, white crystal approximately 1 centimeter by 3 centimeters in dimensions. Forms present on the crystal are $m\ \{10\bar{1}0\}$ and $c\ \{0001\}$. The crystal is in the M. Vonsen collection, Petaluma, California.

Small subhedral crystals with more complex form development were found in cavities in glaucophane schist from Lagunitas Creek, near Nicasio, Marin County. These crystals are colorless and transparent, tabular in habit, and from one millimeter to 3 millimeters in size. Forms observed were: $c\{0001\}$, $m\{10\bar{1}0\}$, $a\{11\bar{2}0\}$, $x\{10\bar{1}1\}$, and $u\{21\bar{3}1\}$.

The physical properties of apatite from several localities were determined, and all gave essentially the same result: Uniaxial (—), ω=1.631, ε=1.634; sp. gravity=3.15.

Chlorite

Chlorite is a widespread, abundant mineral in the glaucophane schists. Optical properties determined on chlorite from five different localities had the following range: 2V=0-10°, β=1.598-1.620, all optically (+). One chemical analysis of chlorite from California glaucophane schist was made by Blasdale,[4] but no optical properties are given. A detailed study of these chlorites is still lacking.

Epidote Group

All of the members of the epidote group, zoisite, clinozoisite, and epidote are found as constituents of the California glaucophane schists.

Zoisite is not abundant in the glaucophane schists in the areas studied. At Tiburon Peninsula it was found as one of the constituents of a medium-grained, massive zoisite-actinolite granulite. In the Camp Meeker area it was found as small, glassy crystals associated with clinozoisite and apatite. The most remarkable locality found for zoisite was on the Syke Ranch, near Laytonville, Mendocino County. Here, in a large glaucophane schist outcrop exposed during road construction, some bladed zoisite crystals up to 2 feet in length were revealed. The optical properties of the zoisite from these three localities are the same, and are as follows: $\alpha=1.696$, $\beta=1.698$, $\gamma=1.701$; opt. (+); $2V=30°$; $r<v$ strong; $Y=b$, $X=c$. Features of note are low birefringence, abnormal blue interference colors in sections perpendicular to Z, and strong dispersion.

Clinozoisite is an important rock-forming mineral of the glaucophane schists. This material is colorless in hand specimen and typically has the following optical properties: $\alpha=1.713$, $\beta=1.722$, $\gamma=1.732$; opt. (+); $2V=85°$; $r<v$ moderate; $Y=b$, $X : c= -2°$.

Epidote (distinctly colored in hand specimen and pleochroic in thin section) is uncommon in the glaucophane schists of California.

Garnet

The garnets of the glaucophane schists of California have been described in detail by Pabst,[5] who shows that there is a considerable difference in composition of the garnets, but that the almandite end-member predominates and is fairly constant (ranged from 48-56 per cent in four different localities). Other end-members are present and their ranges in composition are: grossularite 8-30 per cent, andradite 4-24, and pyrope 10-20 per cent.

Garnet is usually found uniformly distributed throughout glaucophane and pyroxene rocks. The garnet crystals are in general euhedral and attain a maximum size of 1 centimeter. They are usually isolated in a ground-mass of glaucophane or pyroxene, but occasionally have formed as segregations of pure "sugary" garnet in bands up to several centimeters in thickness.

Lawsonite

Lawsonite is a widespread mineral in the California glaucophane schists. It is usually distinctly crystalline and is found in three different habits, either equidimensional, tabular, or prismatic. The crystals are found either embedded in muscovite or chlorite, or growing into open cavities in veins. The tabular crystals are found only as porphyroblasts in lawsonite-chlorite schist. Crystals of the other types are found in both modes of occurrence. The crystals are generally striated and rough. In size they vary from 1 millimeter or less to a maximum of 5 centimeters. Drawings of typical crystals are shown in figure 2.

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[4] Blasdale, W. C., op. cit.

[5] Pabst, A., The garnets of the glaucophane schists of California: Am. Mineralogist, vol. 16, pp. 327-333, 1931.

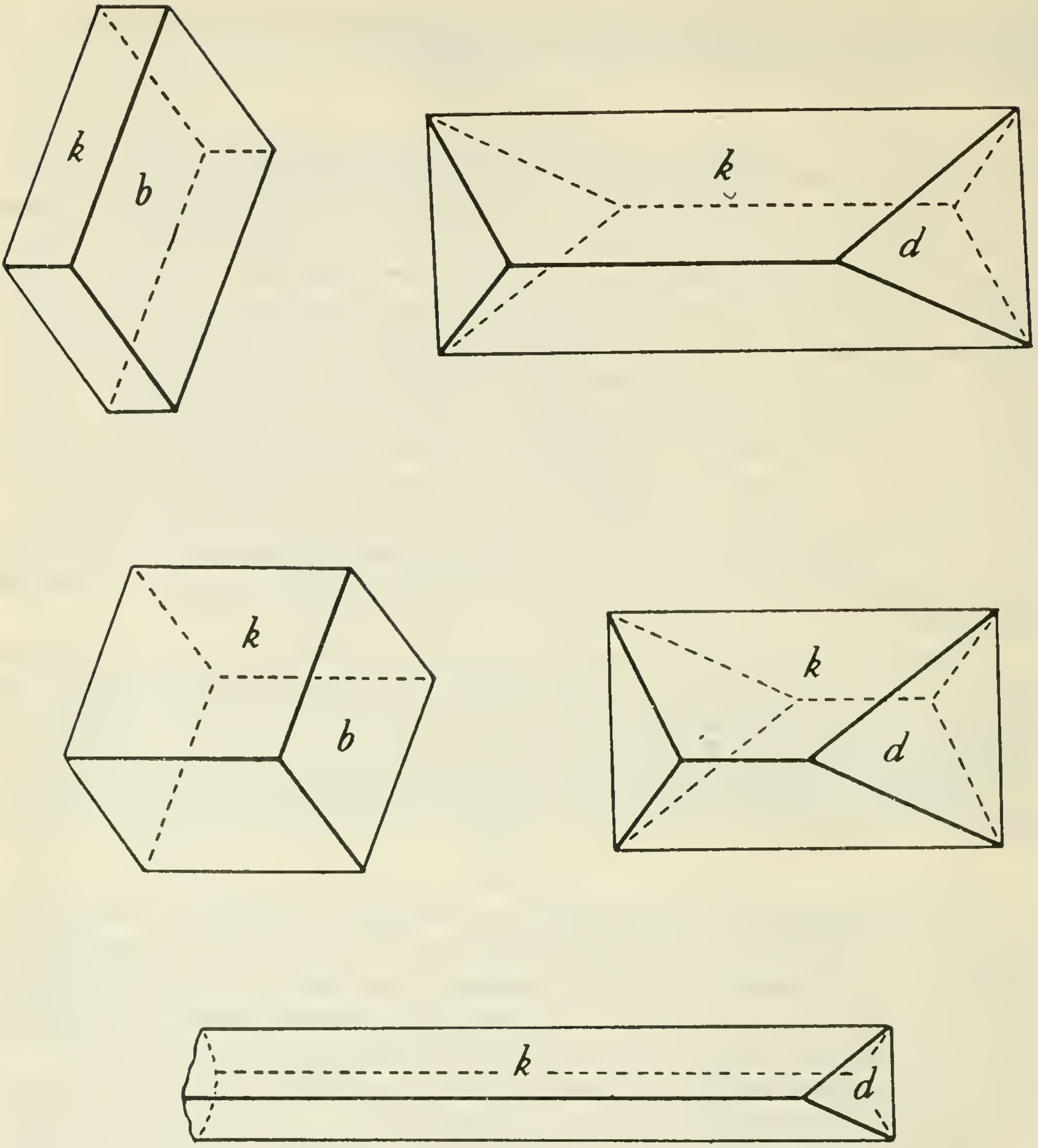

FIGURE 2. Variation in habit of lawsonite crystals from Sonoma County, California

Lawsonite is orthorhombic, rhombic dipyramidal. Structural data have been determined by Gossner and Mussgnug[6] and Wickman.[7] Their results are in essential agreement except for the space group. Wickman's values are as follows: $a=8.88$, $b=5.75$, $c=13.30$ k X, space group C 222. These dimensions rearranged in the conventional order c<a<b are $a=8.88$, $b=13.30$, $c=5.57$ k X, and the corresponding axial ratio is $a:b:c=0.668:1:0.432$.

A new morphological setting has been proposed by Strunz[8] because of non-agreement of x-ray data with the morphological setting chosen by

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[6] Gossner, B., and Mussgnug, F., Röntgenographische Untersuchungen an Prehnit und Lawsonit: Centralbl. Mineralogie, 1931, Abt. A., pp. 422-423.

[7] Wickman, F. E., The crystal structure of lawsonite, $CaAl_2(Si_2O_7)(OH_2)\cdot H_2O$: Arkiv foer Kemi, Mineralogi, och Geologi, vol. 25A, no. 2, 7 pp., 1947.

[8] Strunz, H., Über Kristallography und Chemische Zusammensetzung von Lawsonit und Lievrit: Zeitschr. Kristallographie, Band 96, pp. 504-506, 1937.

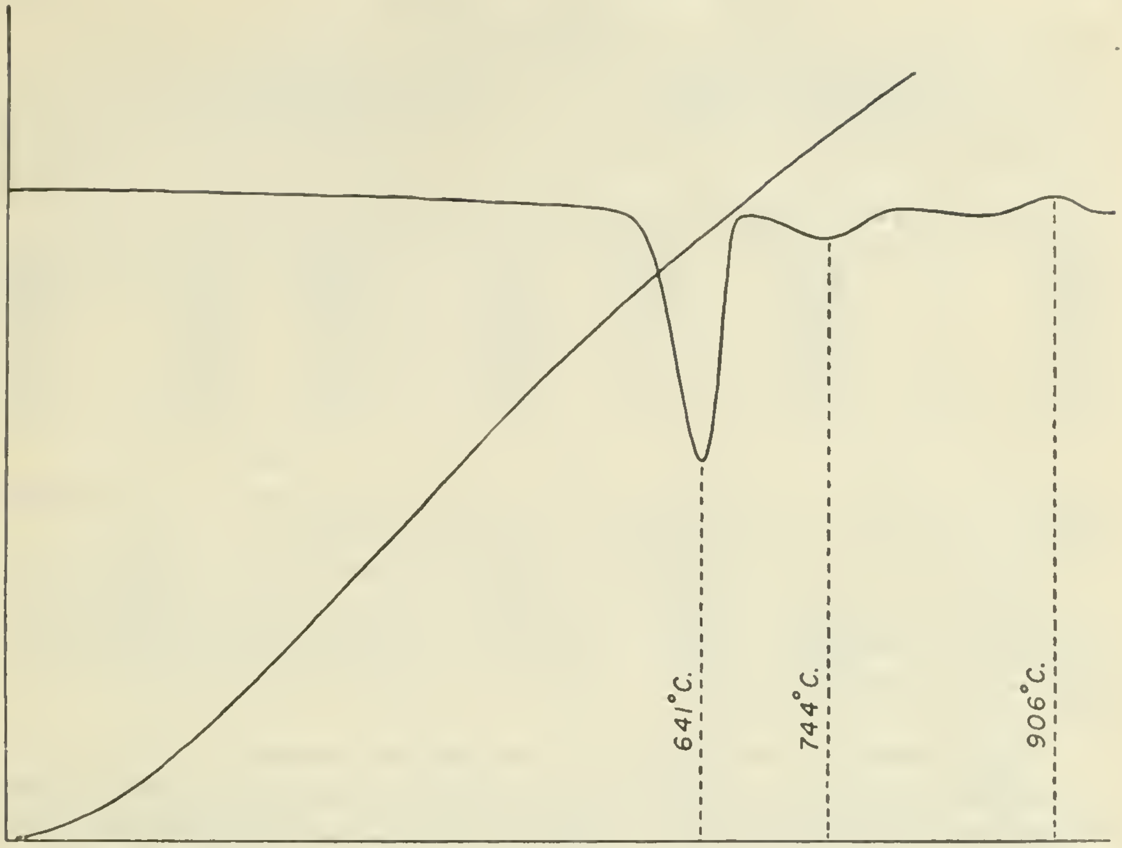

FIGURE 3. Differential thermal curve of lawsonite from near Valley Ford, Sonoma County, California

Ransome.[9] The desirability of the change is further substantiated by the resultant simplification of the indices of the forms in the new setting.

The new morphological setting requires not only a change of position of the unit, but doubling of one of the axial lengths. The transformation is given by 010/002/100. The morphological axial ratio is in good agreement with that derived from the unit cell dimensions, as the comparison given below shows:

$a : b : c = 0.6771 : 1 : 0.4504$ (from morphology)
$a : b : c = 0.668 : 1 : 0.432$ (from unit cell)

A new angle table has been calculated for all known forms on lawsonite, using the elements derived by Ransome, but in the orientation required by the structural study of Wickman (table 5).

Twinning is common on lawsonite, the twin plane being $\{101\}$. Contact twins, made up of two individuals are found, but more commonly the twinning is polysynthetic and seen only under the microscope.

A change in tabulation of some of the physical properties is required by the new morphological setting. The necessary changes are given in table 6.

The cleavage is more easily developed in some specimens than others. For example, long prismatic crystals from Mark West Creek, near Santa Rosa, California, break across their length with an irregular fracture,

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[9] Ransome, F. L., On lawsonite, a new rock-forming mineral from Tiburon Peninsula, Marin County, California: Univ. California. Dept. Geol. Sci. Bull., vol. 1, pp. 301-312, 1893.

Table 5. Lawsonite angle table.

Orthorhombic: dipyramidal — $2/m \quad 2/m \quad 2/m$

$a : b : c = 0.6671 : 1 : 0.4504$ $\qquad$ $p_0 : q_0 : r_0 = 0.6652 : 0.4504 : 1$

$q_1 : r_1 : p_1 = 0.6671 : 1.5033 : 1$ $\qquad$ $r_2 : p_2 : q_2 = 2.2203 : 1.4770 : 1$

	ϕ	ρ	ϕ_1	$\rho_1 = A$	ϕ_2	$\rho_2 = B$
b 010	0°00′	90°00′	90°00′	90°00′		0°00′
a 100	90°00′	90°00′		0°00′	0°00′	90°00′
d 120	36°27′	90°00′	90°00′	53°33′	0°00′	36°27′
e 210	71°18′	90°00′	90°00′	18°42′	0°00′	71°18′
k 101	90°00′	33°38′	0°00′	56°42′	56°22′	56°22′
r 111	61°44′	37°03′	24°14′	57°57′	56°22′	73°25′
s 323	65°42′	36°07′	16°43′	57°30′	56°22′	75°58′

whereas lawsonite from Tiburon Peninsula when broken in the same direction yields a perfect cleavage plane very readily.

Lawsonite from all localities examined was very constant in its refractive index, the maximum variation never exceeding the limits of error of the immersion method (± 0.002). The values obtained from all localities are as follows: $\alpha = 1.665$, $\beta = 1.672$, $\gamma = 1.685$; opt. (+) $2V = 85°$; $X = c$, $Y = a$.

Eight chemical analyses have been made of lawsonite, five of them from California. All are essentially the same and on calculation yield the molecular proportions $CaO.Al_2O_3.2SiO_2.2H_2O$. The formula for lawsonite has been written in various ways, but the recent work of Wickman[10] has shown it is a silicate of the Si_2O_7 type, and the formula should be written $CaAl_2(Si_2O_7)(OH)_2.2H_2O$. Substantiation of correctness of this formula is given by the differential thermal curve shown in figure 3. A large endothermic peak at 641°C. and a smaller one at 744°C. indicate loss of water at two different temperatures, hence two different types of water in the structure. The small exothermic peak at 906°C. is apparently an inversion to another, as yet, unknown structure.

Table 6. Physical properties of lawsonite.

	Old	New
Cleavage	$\{010\}$ perfect $\{001\}$ perfect $\{110\}$ imperfect	$\{100\}$ perfect $\{010\}$ perfect $\{101\}$ imperfect
Optical orientation	$X = a$ $Y = b$ $Z = c$	$X = c$ $Y = a$ $Z = b$

Mica Group

The mica group is represented in the California glaucophane schists by three members, muscovite, fuchsite, and biotite. Of these muscovite is the most important since it is one of the most abundant minerals composing the rocks of the glaucophane schist group. Fuchsite and biotite are found only in small amount in widely scattered localities.

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[10] Op. cit.

The mica associated with lawsonite from Tiburon Peninsula was first described as margarite (brittle mica group) by Ransome.[11] Later it was found to be normal muscovite.[12] All other white mica examined by the writer from every rock type in the schist group has also proved to be muscovite.

One complete and two partial analyses of muscovite from the California glaucophane schists are now available. These are given in table 7, together with their optical properties.

Table 7.—Muscovite from California glaucophane schists

	1	2	3
SiO_2	48.42		
Al_2O_3	28.41		
FeO	2.10		
CaO	0.48		
MgO	3.8[illegible]		
Na_2O	1.95	0.52	1.22
K_2O	10.36	10.11	[illegible]
H_2O	4.72		
	101.25		
β	1.597	1.598	1.597
Opt. char.	(−)	(−)	(−)
2V	15°	15°	[illegible]

1. Muscovite associated with lawsonite, Reed's Station, Tiburon Peninsula.[1] E. S. Larsen, analyst.

2. Muscovite from a muscovite glaucophane schist, Porter Creek, Sonoma County. F. A. Gonyer, analyst.

3. Muscovite from diopside garnet granulite, Mill Creek, Sonoma County. F. A. Gonyer, analyst.

[1] Eakle, op. cit.

There seems to be no essential difference in the muscovite of different associations. In fact, and contrary to what one might expect, the muscovite from a rock composed entirely of muscovite and glaucophane contains less than Na_2O than that from a rock containing no glaucophane.

Pumpellyite

Pumpellyite was first described in 1925 by Palache and Vassar[13] from the Keweenaw Peninsula, Michigan. Since then it has been found in several other localities in various parts of the world. M. Vonsen in 1932 found pumpellyite to have widespread occurrence in the California glaucophane schists.

The formula of pumpellyite has been written in various ways, based upon five chemical analyses. Six analyses are now available, but the most recent one is incomplete. These analyses, together with optical properties are given in table 8.

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[11] Op. cit.

[12] Eakle, A. S., Notes on lawsonite, columbite, beryl, barite, and calcite: Univ. California, Dept. Geol. Sci. Bull., vol. 5, pp. 81-94, 1906.

[13] Palache, C., and Vassar, H. E., Some minerals of the Keweenawan copper deposits: pumpellyite, a new mineral; sericite; saponite: Am. Mineralogist, vol. 10, pp. 412-418, 1925.

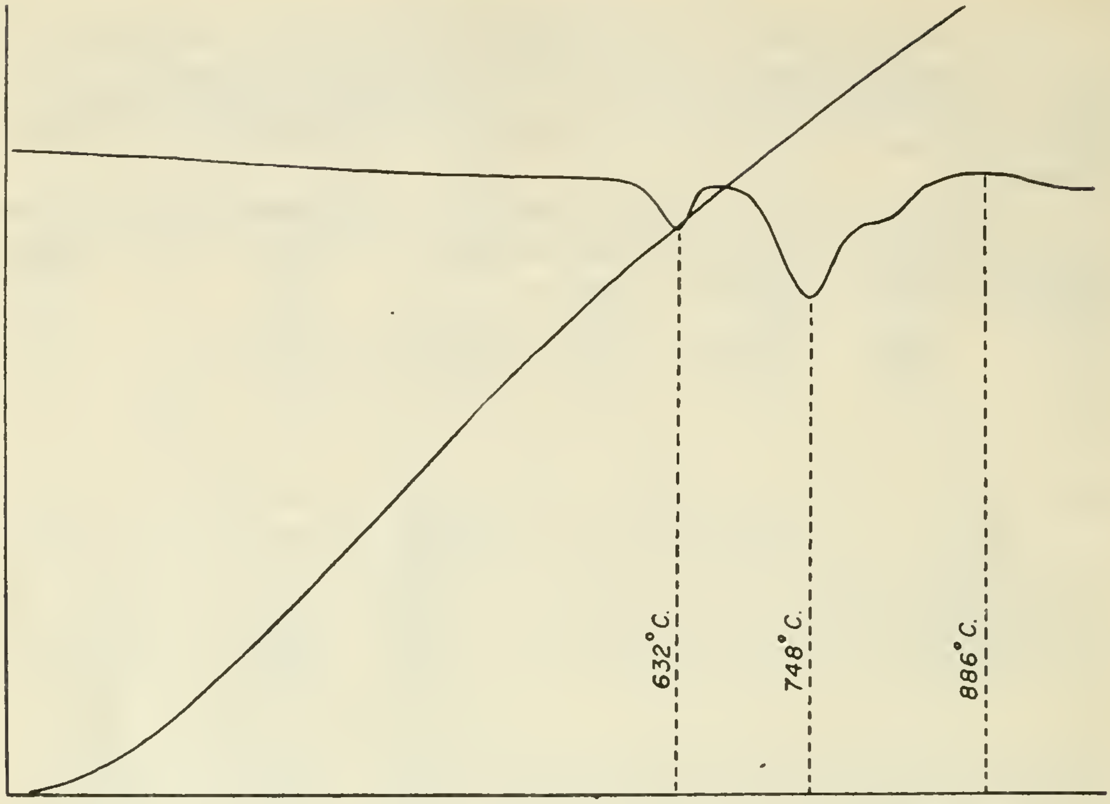

FIGURE 4. Differential thermal curve of pumpellyite from Porter Creek, Sonoma County, California

Calculation of the original analysis by Palache and Vassar[14] yielded the formula $6CaO.3Al_2O_3.7SiO_2.4H_2O$. Irving, Vonsen, and Gonyer[15] showed that by redistribution of the isomorphous elements in calculation of the atomic proportions a formula could be obtained which fitted the analyses more closely. Their formula was written $Ca_4Al_6Si_6O_{23}(OH)_3.2H_2O$. Berman[16] since proposed the formula $Ca_4Al_6Si_6O_{24}(OH).H_2O$ in order to indicate the similarity of pumpellyite to epidote.

To aid in the correct interpretation of the role of the water in the pumpellyite structure a differential thermal analysis was made. This curve is reproduced in figure 4. It will be seen that there are distinct endothermic peaks at 632°C. and 748°C., indicating that water is present in part as $(OH)^-$ and in part as H_2O. The formula of either Irving, Vonsen, and Gonyer, or Berman, might therefore be correct. The necessity of further structural study is indicated.

Figure 5 shows the total iron content of the analyzed pumpellyite given in table 8 plotted against index of refraction. A good straight line relation is obtained indicating that the increase in index is largely a function of the amount of iron present. A smooth curve is obtained only when total iron is plotted. Either ferrous or ferric iron separately do not vary in a regular manner.

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[14] Op. cit.

[15] Op. cit.

[16] Berman, H., Constitution and classification of the natural silicates: Am. Mineralogist, vol. 22, pp. 342-408, 1937.

Table 8. Pumpellyite.

	1	2	3	4	5	6
SiO_2	37.63	38.01	37.53	37.18	36.51	36.9
TiO_2	0.41	0.21	0.14	------	------	------
Al_2O_3	27.14	25.88	25.39	23.50	24.11	27.7
Fe_2O_3	------	1.11	1.74	5.29	3.50	9.0
FeO	3.25	2.90	2.95	2.09	5.14	
MnO	1.03	0.17	0.13	0.13	0.15	------
MgO	1.47	1.81	2.65	3.18	4.70	1.0
CaO	21.49	22.70	22.56	23.08	20.16	22.4
Na_2O	0.46	0.46	0.58	0.19	------	------
K_2O	0.08		none	trace	1.4	------
NiO	------	------	------	------	trace	------
CuO	------	------	------	------	0.19	------
P_2O_5	------	------	trace	------	------	------
B_2O_3	------	------	------	------	------	0.6
$H_2O(-)$	0.12		0.09	0.06	------	------
$H_2O(+)$	7.27	6.64	6.73	6.28	3.67	------
	100.35	99.89	100.13	100.97	99.73	97.6
α	1.677	1.679	1.686	1.698	------	variable
β	1.678	1.680	1.690	1.700	------	1.693
γ	1.690	1.692	1.698	1.708	------	to 1.726
Birefr.	0.013	0.013	0.012	0.010	------	------
Opt. char.	(+)	(+)	(+)	(+)	------	variable
2V	38°	40°	------	large	------	variable
Disper.	$r < v$ strong	$r < v$ strong	$r < v$ strong	$r < v$ strong	------	variable
Orient.	$Y = b$ $X:a = 12°$	$Y = b$ $X:a = 12°$	$Y = b$ $X:a = 12°$	$Y = b$	------	variable
Color	brown	green	green	green	------	green
X	colorless	colorless	colorless	colorless	------	pale-green
Y	brown-yellow	pale-green	light-green	green	------	blue-green
Z	colorless	colorless	colorless	colorless	------	brown-yellow
Sp. gr.	3.22	3.18	3.2	------	------	3.23-3.32

1. Skaggs Springs, California. F. A. Gonyer,[1] analyst.
2. Porter Creek, California. (The original paper incorrectly gives the locality as Mill Creek). F. A. Gonyer,[2] analyst.
3. Asahine, Tukikawa-mura, Titibu-gori, Saitama Prefecture, Japan.[3] S. Tanaka, analyst.
4. Keweenaw Peninsula, Michigan. H. E. Vassar,[4] analyst.
5. Keweenaw Peninsula, Michigan. H. E. Vassar,[5] analyst.
6. Witwatersrand, Union of South Africa.[6] Partial analysis by C. F. J. Van der Walt.

Pumpellyite from the glaucophane schists of California is characteristically twinned. The twins are simple contact twins, and may be seen only in thin section. The twin plane is probably $\{001\}$.

In the California glaucophane schists pumpellyite is always a vein mineral, often in sharp, narrow veins cutting directly across the schistosity planes of the rock. Occasionally the veins are vuggy and contain very rough crystals made up of semi-radiating sheafs of fibers.

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[1] Irving, J., Vonsen, M., and Gonyer, F. A., Pumpellyite from California: Am. Mineralogist, vol. 17, pp. 338-342, 1932.

[2] Irving, Vonsen, and Gonyer, op. cit.

[3] Tsuboi, S., Pumpellyite from Asahine, Tukikawa-mura, Titibu-gori, Saitama Prefecture: Japanese Jour. Geology and Geography, vol. 13, p. 333, 1936.

[4] Palache and Vassar, op. cit.

[5] Palache and Vassar, op. cit.

[6] de Villiers, J. E., Optical properties and crystallography of zoned pumpellyite from Witwatersrand: Am. Mineralogist, vol. 26, pp. 237-246, 1941.

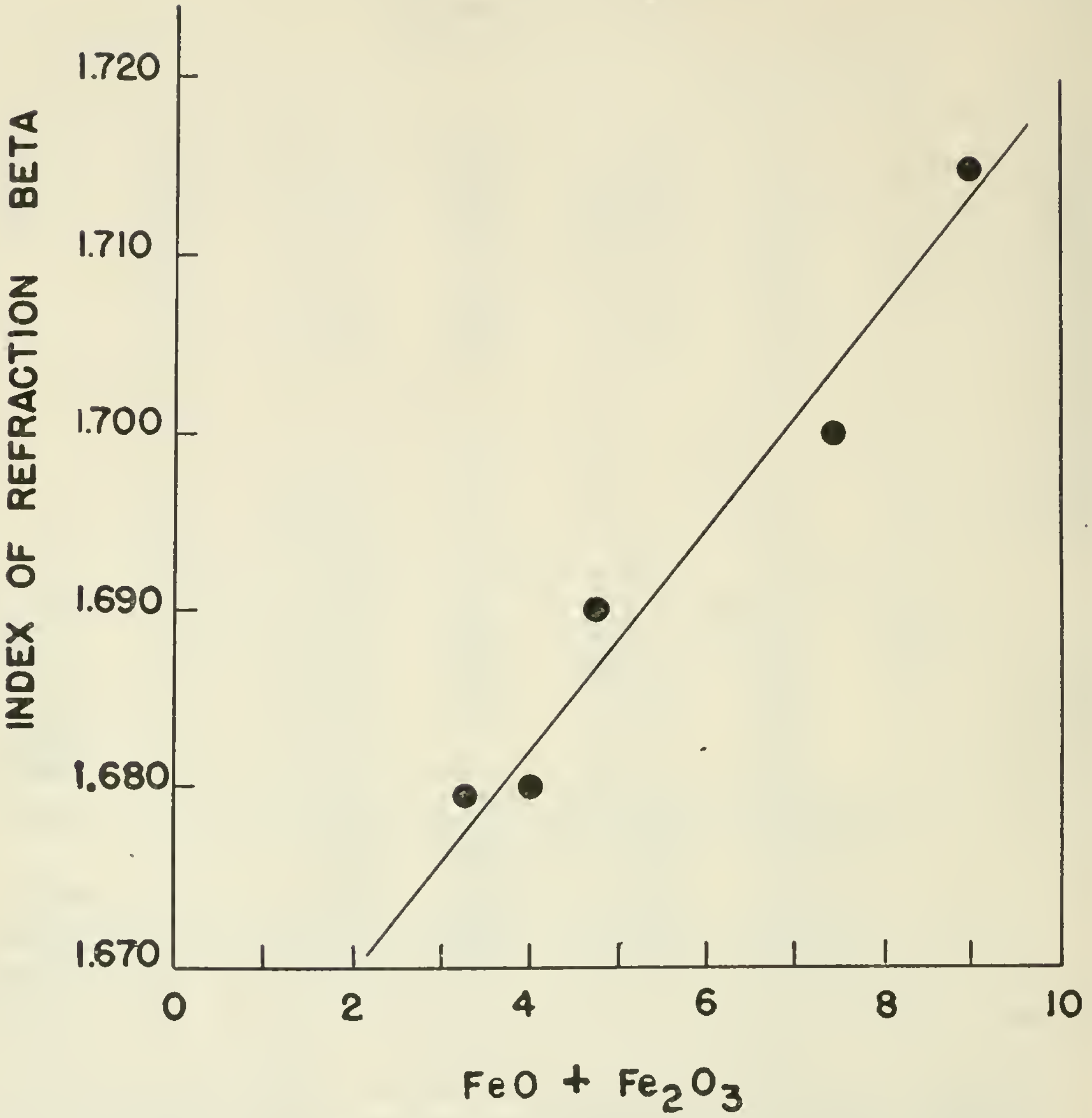

FIGURE 5. Graph showing relation of index of refraction to total iron content in weight percent of pumpellyite

Pyroxene (Diopside-Jadeite)

Deep green pyroxene is an abundant constituent of several rock types in the glaucophane schist group. It is an essential constituent of glaucophane-pyroxene rocks and pyroxene-garnet rocks. It is found principally in anhedral grains, but occasionally as rough crystals projecting into vugs.

An analysis was made of the pyroxene from a pyroxene-garnet granulite from Mill Creek, Sonoma County. It proved to be a soda-rich pyroxene, a member of the diopside-jadeite series commonly called omphacite.[17] No analyses are available of the pyroxene from the other rock types. However, the optical properties of the pyroxene from all rock types of the glaucophane schist group are identical, and it seems reasonable to assume that all the pyroxene present in these rocks is diopside-jadeite.

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[17] Since this paper was completed material near the jadeite end of the diopside-jadeite series has been found in a number of localities.

The analysis and optical properties of the California diopside-jadeite are given in table 9, column 1. For comparison are given three analyses of pyroxenes from eclogites of Norway.

Table 9. Diopside-jadeite from California and Norway.

	1	2	3	4
SiO_2	53.31	48.61	55.56	54.03
TiO_2	0.26		0.15	0.54
Al_2O_3	10.52	14.60	7.17	11.54
Fe_2O_3	4.11		2.82	5.62
FeO	2.84	10.46	2.06	4.09
MnO	0.05		0.05	0.05
MgO	8.42	9.66	11.32	5.13
CaO	14.50	13.32	16.85	11.82
Na_2O	5.90	2.07	3.92	6.81
K_2O	0.05	0.42	0.57	0.20
$H_2O(+)$	0.16		0.08	0.29
	100.12	99.14	100.55	100.12
Jadeite	40	13	25	44
Diopside	60	87	75	56
α	*1.673			
β	1.679	1.685	1.683	1.679
γ	1.691			
Biref.	0.018	0.018	0.024	
Opt. char.	(+)	(+)	(+)	(+)
2V	60°	60°	67°	82°
Orient.	$Y = b$ $Z{:}c = 39°$		$Y = b$ $Z{:}c = 42°$	$Y = b$ $Z{:}c = 41°$
Disper.	r > v weak	none	r > v weak	r > v weak
Sp. gr.	3.34 (+0.02)	3.34	3.330	3.365

1. Diopside-jadeite—from pyroxene-garnet granulite near the Junction School House, Mill Creek area, Healdsburg quadrangle, California. F. A. Gonyer, analyst.
2. Omphacite—from eclogite near Saltkajael, Nordfjord, Norway.[1] L. Thomassen, analyst.
3. Omphacite—from eclogite near Silden, Nordfjord, Norway. P. Eskola,[2] analyst.
4. Omphacite—from eclogite near Vanalvsdalen, Sondmore, Norway.[3] L. Thomassen, analyst.

* Indices of refraction ± 0.002.

[1] Eskola, P., On the eclogites of Norway: Vidensk. Skr. I Mat. Naturv. Kl., no. 8, pp. 1-118, 1921.

[2] Eskola, op. cit.

[3] Eskola, op. cit.

Quartz

Quartz is an abundant mineral of the glaucophane schists. It is the major constituent of some rock types of the schist group, such as glaucophane-garnet-quartz granulite, in which it makes up the fine-grained granular groundmass of the rock.

A minor occurrence of quartz in the schists is as narrow veins of milky quartz cutting glaucophane schist.

Rutile

Rutile is a widespread accessory mineral in the glaucophane schists. It is most commonly seen only in thin sections, as small, dark, reddish-brown grains, either alone or associated with sphene.

Rutile crystals of unusual size may develop in the schists. At Tiburon Peninsula dark reddish-brown crystals approximately 2 by 20 millimeters, were found in glaucophane schist. On the Syke Ranch, near Laytonville, Mendocino County, single crystals as much as 5 by 60 millimeters in size were found. The largest crystal seen from the California glaucophane schists, also from the Syke Ranch, measured 2 by 7 centimeters.

Sphene

Sphene, like rutile, is an abundant accessory mineral in the glaucophane schists. It is most commonly seen in thin section, as small anhedral to subhedral crystals. Occasionally it has developed into large crystals, the largest seen being subhedral crystals up to 4 centimeters across, from Mill Creek, Sonoma County.

In thin section the sphene is colorless. Megascopically it is pale yellow in color, often clear and transparent.

Sulfides

Simple sulfides of iron and copper are occasionally found in minor amount disseminated throughout glaucophane schists. Of these pyrite is the most abundant. Rarely chalcopyrite and covellite are found.

The best development of pyrite was found on the east side of Tiburon Peninsula. Here an outcrop of actinolite-talc-garnet rock contains sharp cubes of pyrite up to 1 centimeter in size.

The only noteworthy occurrence of chalcopyrite and covellite observed was on the Syke Ranch, Mendocino County. Here small, irregular blebs of these sulfides were found in glaucophane schist.

Talc

Talc is a minor constituent of the glaucophane schists. It is found in widely scattered localities as white to pale green masses, with actinolite. In the Mill Creek area it was found as nodular masses of nearly pure talc up to 2 feet in diameter, in glaucophane schist. This talc has the following optical properties: (—) $2V=0°$, $\alpha=1.542$, $\beta=1.590$, $\gamma=1.590$.

PARAGENESIS

The general impression gained, after even a brief examination of the California glaucophane schists, is that they have been strongly affected by hydrothermal activity. They exhibit great variability in grain size, their mineralogy changes sharply within short distances, and veining is a common feature.

The 30 different minerals found in the glaucophane schists in the areas studied were not developed simultaneously, but were successively introduced over a considerable time interval. Evidence of the paragenetic history through which these rocks have passed is found in almost every specimen. However, certain localities gave more abundant data than others, and these will be described in the following section.

Mill Creek WPA Quarry

This quarry was excavated by the Works Progress Administration in a large outcrop of glaucophane schist in the Mill Creek Area, Sonoma County, a quarter of a mile east of the Junction School House, on the Mill Creek road.

The main mass of this large schist outcrop is diopside-jadeite-garnet granulite. All other minerals present make up a small percentage of the whole. The minerals present, in the order in which they formed are: diopside-jadeite, garnet, muscovite, hornblende, glaucophane, rutile, sphene, chlorite, and pyrite.

Diopside-jadeite and garnet crystallized together, the garnet having formed as euhedral crystals in a granular groundmass of pyroxene. There is a small amount of muscovite present, and it is commonly concentrated about the garnet crystals.

A second set of minerals is clearly later than the main rock mass. These are: hornblende, glaucophane, rutile, sphene, chlorite, and pyrite. These minerals are undoubtedly later because their occurrence is almost entirely restricted to narrow seams or fractures irregularly traversing the massive granulite.

The hornblende, a bluish-green variety, is seen in hand specimen to be concentrated along narrow fractures and in thin section about garnet crystals. Glaucophane is also found along fracture planes in the main rock mass and has often formed as peripheral zones about hornblende. Chlorite is also strongly concentrated along narrow fractures with sphene, glaucophane, hornblende, and pyrite. In thin section, chlorite can be seen replacing garnet and hornblende. The sphene forms pale yellow subhedral crystals up to 1 centimeter in size, associated with smaller amounts of rutile. Pyrite is common and is also restricted in its appearance to the seams of late-formed minerals.

Occidental WPA Quarry

This quarry is in the Camp Meeker area, 2 miles east of Occidental. The quarry was excavated by the Works Progress Administration and some very good exposures resulted.

The first impression gained upon examination of the exposures in the quarry is the intensity of the hydrothermal action. Great variation in rock type over a short space and an abundance of coarsely crystallized vein minerals and segregations are a striking feature.

Thirteen minerals were found in the quarry, and although it was not possible to determine all of the details accurately, the approximate sequence of mineralization is as follows: diopside-jadeite, garnet, hornblende, muscovite, clinozoisite, zoisite, apatite, actinolite, glaucophane, pumpellyite, sphene, chlorite, and pyrite.

Diopside-jadeite and garnet were clearly the first minerals formed, crystallizing together as massive, dark-green granulite. The garnets reach a maximum size of 2 millimeters and compose 30 to 50 per cent of the rock.

Part of the rock exposed in the quarry is dark-green almost black, massive hornblende-garnet granulite. This rock was probably formed at about the same time as the diopside-jadeite-garnet granulite. Some glaucophane is present in the amphibolite in minor amounts, as thin peripheral zones about part of the hornblende

Muscovite is found in small amount, in part uniformly dispersed throughout the granulite, in part concentrated in seams. Clinozoisite is very abundant, commonly in nearly pure seams and segregations. Disconnected irregular patches of diopside-jadeite granulite are present in the clinozoisite, clearly remnants due to partial replacement. The garnet of the granulite remnants has been completely replaced by chlorite.

Intimately associated with clinozoisite are small amounts of zoisite and apatite. In hand specimen the clinozoisite is pale yellow-green in color and the zoisite colorless. The exact relation between them is not known.

Actinolite was found in pure concentrated masses up to 20 centimeters in diameter. Other specimens consist of actinolite and chlorite, and the chlorite is replacing actinolite.

Glaucophane-clinozoisite-muscovite schist is an abundant rock at the locality. The only certain fact known about the glaucophane here is that it is later in age than the hornblende.

Pumpellyite was found in one place in the quarry, as a narrow vein cutting glaucophane schist.

Chlorite, sphene, and pyrite are found in veins and seams, clearly late minerals but their exact age relations are not known.

Porter Creek Pumpellyite Locality

The Porter Creek area is the locality from which pumpellyite was first described in California by Irving, Vonsen, and Gonyer.[18] The locality is part of a large area of schist, a localized zone in which mineralization was unusually varied. The outcrop from which the specimens described were collected is on a serpentine contact, near the northeast corner of section 19, T. 8 N., R. 9 W., M.D., Healdsburg quadrangle, Sonoma County.

Eleven different minerals were found, and their approximate sequence of mineralization is as follows: diopside-jadeite, muscovite, clinozoisite, rutile, sphene, glaucophane, pumpellyite, lawsonite, albite, calcite, and quartz.

The main mass of rock is highly schistose, medium-grained glaucophane-muscovite-diopside-jadeite schist. Occasional narrow bands in the rock, following the planes of schistosity, are made up largely of clinozoisite. Other narrow bands, or layers, are characterized by a concentration of more coarsely crystalline muscovite containing abundant glaucophane needles. Seen only in thin section are occasional rutile grains and more abundant grains of sphene.

There are several vein minerals, of which pumpellyite is clearly the first. It has formed in numerous veins, either concordant with, or transgressing the planes of schistosity of the rock. Some of the veins have even, parallel walls and reach a maximum width of about 3 centimeters. Other pumpellyite veins pinch and swell and are not continuous for more than a few centimeters. They are frequently vuggy, but no good crystals were found. The pumpellyite is fibrous and the fibers are roughly perpendicular to the vein walls.

The age of the lawsonite is clearly shown by veins of lawsonite cutting cleanly across pumpellyite veins. Composite veins of pumpellyite and lawsonite are also found, with lawsonite always in the interior and pumpellyite lining the vein walls. The lawsonite veins are in part parallel to, and in part cutting across the schistosity. The veins have sharp contacts and reach a maximum width of 1 centimeter. Good crystals were found in numerous cavities.

On one specimen a few small albite crystals were found encrusting lawsonite on the wall of a small cavity. Vugs in the pumpellyite and lawsonite veins are locally filled with calcite. One specimen showed a vein of milky quartz cutting sharply across the plane of schistosity of the rock, but revealed nothing further as to the relation of the quartz to the other minerals.

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[18] Op. cit.

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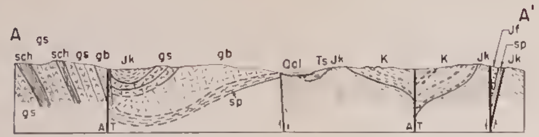

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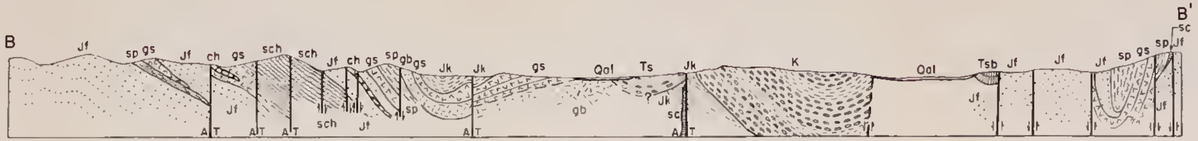
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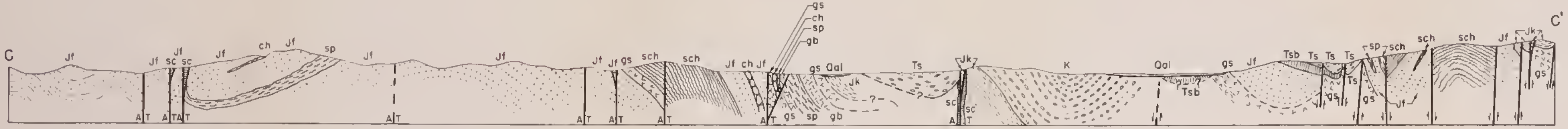
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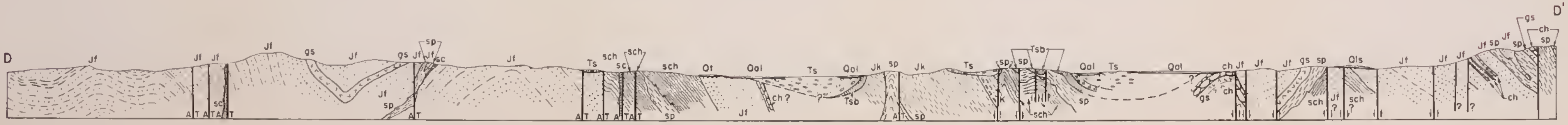
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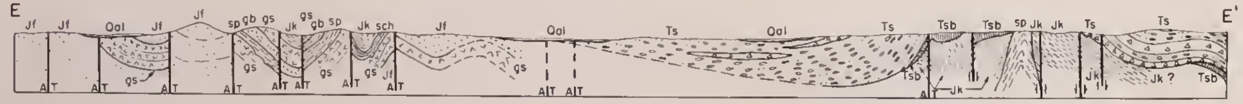
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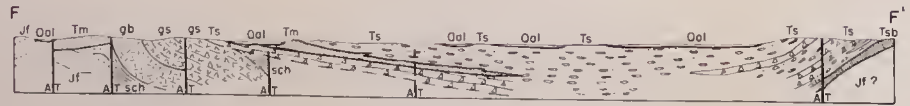

SECTION FF'

GEOLOGIC SECTIONS ACROSS THE HEALDSBURG QUADRANGLE, CALIFORNIA

By William Kelso Geoley

EXPLANATION

QUATERNARY

- Qls Landslide
- Qal Alluvium
- Qt Terrace

TERTIARY — PLIOCENE

- Tm Merced formation
- *Sonoma group*
  - Ts Gravel, sand, and clay, interbedded tuff
  - Tsb Basalt

CRETACEOUS (?)

- K Conglomerate

UPPER JURASSIC

- Jk Knoxville formation
- *Franciscan group*
  - sch Schist
  - sp Serpentine
  - gb Gabbro and diabase
  - gs Greenstone
  - ch Chert
  - Jf Sandstone and shale

- sc Silica carbonate

Fault, arrows show relative directions of movement

A|T Strike-slip fault, A = relative movement away from observer; T = toward observer

POST-JURASSIC DIASTROPHIC EVENTS IN THE CALIFORNIA COAST RANGES

		CENTRAL COAST RANGES (after Taliaferro, 1941)	SAN FRANCISCO AREA AND NORTHERN COAST RANGES (after Lawson, 1914 & Calif. Div. Mines Bull. 118)	COAST RANGES NORTH OF SAN FRANCISCO BAY (after Weaver, 1949)	TENTATIVE CORRELATIONS HEALDSBURG QUADRANGLE (Gealey)
RECENT		MOVEMENT ON SAN ANDREAS FAULT.	MOVEMENT ON SAN ANDREAS AND HAYWARDS FAULTS.	Late Pliocene-early Quaternary diastrophism continuing in varying and lesser degree to the present day.	Slight uplift and renewed downcutting by Russian River. STRIKE-SLIP FAULTING
PLEISTOCENE	Upper	?	Variable uplift and depression, submergence in San Francisco Bay area. ?		Slight subsidence, drowning of Russian River and valleys to south. Last broad alluvial flat formed. Uplift of about 200 feet. Subsidence of 150 feet, terrace fill of 200 foot level. CONTINUED UPLIFT - coastal terraces elevated to 1520 feet.
	Middle	STRONG COMPRESSION, folding, thrust faulting; accentuation of upper Pliocene orogeny.	POST-ALAMEDA DIASTROPHISM (of Lawson). Major block faulting; present range outlines determined.		BEGINNING OF UPLIFT OF RANGES; dip-slip faulting and warping of erosion surface. ?
	Lower				Development of post-Merced erosion surface? Gentle folding of Sonoma-Merced.
PLIOCENE	Upper	STRONG COMPRESSION, folding, thrust faulting; uplift of ranges.	STRONG COMPRESSION, folding of Orinda-Siesta and Petaluma formations; uplift of ranges.	Strong deformational movements.	
	Middle		?	Strong folding and local thrusting following Petaluma deposition; deep erosion.	Pre-Sonoma peneplanation.
	Lower	Much land above sea level; Santa Lucia and Diablo Ranges higher northward. Local folding and faulting; locally gradational.		Earth movements of considerable intensity.	? No data
MIOCENE	Upper	Slight folding, angular discordance to 11°. IMPORTANT DIASTROPHISM; compression, folding, uplift, and erosion. Separate basins of deposition	No data Marked discordance; folding, erosion.	Differential minor crustal movements.	? No data ? No data
	Middle				? No data
	Lower	Unconformity.	? Middle Miocene unconformable on older rocks at Point Reyes, Fort Ross, Covelo; MAJOR OROGENY?	Erosion during lower Miocene.	?
OLIGO.		Red beds Unconformity usually. NORMAL FAULTING of great magnitude, ancestral San Andreas fault formed; folding. Final breakup of Mesozoic geosyncline.	Unconformity. Unconformity.		INFAULTING of Little Sulfur graben and Geyserville syncline-Fitch Mountain area. MAJOR FOLDING of Mesozoic rocks on N. 70° W. trend.
EOCENE	Upper	Emergence; slight folding and faulting.	Unconformity.	Subsidence following Domengine. Minor deformation at close of Domengine time.	
	Middle	Widespread sinking, some folding and faulting.	Unconformity.		No data
	Lower	Widespread withdrawal of seas; marked break over most of Coast Ranges.	Disturbance and uplift; moderate erosion.		No data
PALEOC.		Weak uplift, tilting, probably folding; slight angular discordance. North Santa Lucia Range uplifted?	Weak upwarping and erosion; unconformity.	Differential downwarping beginning in early Paleocene. Local warping late in Chico time and erosion to form slight unconformity.	No data
CRETACEOUS	Upper	SANTA LUCIAN OROGENY in Santa Lucia and southern Diablo ranges; strong folding, angular discordance to 80°; erosion. MID-CRETACEOUS DISTURBANCE; folding and overlap; Jurassic and lower Cretaceous basin fragmented. Gabilan Range raised and stripped.	Uncertain Overlap along west side of Sacramento Valley and within ranges.	Late middle Cretaceous diastrophism.	? -?- Warping of Knoxville before upper Cretaceous deposition. ?
	Lower	DIABLAN OROGENY; uplift, erosion, overlap.	DIABLAN OROGENY; uplift, erosion, overlap.		
JURASSIC	Upper			Slight elevation western part of Coast Range basin during Knoxville epoch.	

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